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INFORMATION ANALYSIS CENTER

INTRODUCTION TO

PRECISION GUIDED MUNITIONS

A HANDBOOK PROVIDING TUTORIAL INFORMATION AND DATA ON PRECISION GUIDED MUNITIONS (PGM)

R. J. HEASTON
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This volume contains general tutorial information on smart weapons (precision guided munitions and guided missiles), how they work, what goes into their design, and their future trends. The material is intended to provide an overview of the technology involved in the design and operation of precision guided munitions for the non-technical reader. The various types of guidance are explained and the major components of a guided missile are discussed.

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VOL. 1: TUTORIAL

(REVISED EDITION)

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INTRODUCTION TO PRECISION GUIDED MUNITIONS

A Handbook Providing Tutorial Information And Data on Precision Guided Munitions (PGM)

Precision Guided Munitions (PGM), or smart weapons, are a new dimension in warfare. A smart weapon is one that can change its direction in flight based upon new information on where it is going. The purpose of this handbook is to explain in a fairly simple manner how smart weapons achieve their precision guidance.

This volume presents some of the basic concepts and techniques used in the design and operation of guidance systems. It is intended to provide background information for those interested in this general area, and has been prepared with such readers in mind. It does not contain mathematical analyses or go into technical detail. To do so in such a broad area would require a much larger treatise and address a different audience.

PREFACE

1. INTRODUCTION

The idea for this handbook, as well as its basic design, layout, and much of its first draft were conceived and written by Dr. Robert J. Heaston, Technology Manager for the Director of Weapons Systems of the Army, Office of the Deputy Chief of Staff for Research, Development, and Acquisition. He was also the first Chairman of the Joint Services Guidance and Control Committee (JSGCC), under whose direction this handbook was prepared. Members of the Executive Committee of the JSGCC assisted in obtaining data for Volume 2 of the Handbook. Overall preparation of the handbook was performed by the Guidance and Control Information Analysis Center (GACIAC), under the direction of Mr. Charles W. Smoots, who supplemented and revised the tutoral material and edited the entire handbook.

2. JOINT SERVICES GUIDANCE AND CONTROL COMMITTEE

2.1 Creation

The Joint Services Guidance and Control Committee (JSGCC) was created by Department of Defense Instruction (DODI) 5154.26, 19 March 1976 (Amended, 15 November 1976) to coordinate the overall defense efforts in tactical missile weapons terminal homing technology. The following fields of interest for the JSGCC are spelled out in the DODI: The Joint Committee shall concern itself with the technology of tactical weapon guidance and control and related analysis, hardware, subsystems and systems. Tactical weapons shall include, but not be limited to missiles, bombs, submunitions, and projectiles having nonnuclear warheads and/or those pertinent weapons with nuclear warheads whose primary application is designated to be tactical by the intended user. The guidance and control of munition dispersing cannisters shall also be included. Technical areas of interest shall include: instrument and seeker development and test; manufacturing process development; subsystem and system simulation; development of computational techniques and hardware; control actuators and power sources, aerodynamic and reaction jet control devices; inertial components and system developments; special test equipment and

techniques; theoretical performance computations; analytical test techniques; component design criteria; operational serviceability; environmental protection; and materials areas specifically related to weapon guidance and control.

2.2 Organization

The Executive Committee of the JSGCC is made up of representatives from the Army, Navy, Air Force, Marines, Office of the UnderSecretary of Defense for Research and Engineering, Defense Advanced Research Projects Agency, Defense Mapping Agency, Defense Logistics Agency, and Defense Nuclear Agency. The JSGCC performs its mission through exchange and coordination of guidance and control program and technical data, visits to DOD facilities, national meetings, working groups, and products of the Guidance and Control Information Analysis Center (GACIAC).

Working Groups are established to consider specific areas and are dissolved after completing their assignment. This gives the committee the flexibility to handle the diverse variety of topics related to their area of responsibility. A list of current members of the Executive Committee and Working Groups may be obtained from GACIAC.

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VOLUME 1: GUIDANCE AND CONTROL TUTORIAL

1. INTRODUCTION

Precision guided munitions (PGMs) or smart weapons are so new to modern warfare that few people really understand what they are or how they work. This understanding is complicated by a new jargon which technologists use to describe different smart weapons. The purpose of this tutorial is to help those interested in this technology understand and better appreciate smart weapons. The complexity of smart weapons and the extent of the associated jargon is summarized in Figure 1. Most of the variables which contribute to different operating characterisitics of PGMs are indicated. This figure will be referenced throughout this tutorial. An attempt will be made to define each term or to relate the term to some unique PGM characteristic. Moreover, much of the vocabulary used to describe smart weapons will be taken from this figure. Diagrams of the operational characteristics of different PGMs, provided in Volume 2 of this handbook, will use the same language as contained in Figure 1. Any other special terminology is defined in a glossary at the end of the tutorial.

The advent of precision guided munitions has created a proliferation of jargon relative to smart weapons. This jargon has brought an avalanche of new acronyms with it. References are made to smart munitions, brilliant munitions, self contained munitions, tank smart munitions (TSM), heavy mortar smart munitions (HMSM), terminally guided submunitions (TGSM), enhanced submunitions, and improved sensing munitions (ISM). There are all sorts of smart projectiles: mortar launched guided projectile (MLGP), guided anti-armor mortar projectile (GAMP), air defense guided projectile (ADGP), tank launched guided projectile (TLGP), conventional geometry smart projectile (CGSP), cannon launched guided projectile (SSGP), tube launched guided projectile (TLGP), spin stabilized guided projectile (SSGP), fin stabilized guided projectile (FSGP), medium artillery terminal homing projectile (MATH-P), smart tank projectile (STP), terminally guided projectile (TGP), and simply guided projectile - experimental (GPX).

OPERATIONAL FUNCTIONS

Surveillance - Acquisition - Tracking - IFFN - Launch - In Flight - Terminal - Kill Assessment

TARGET SENSING GUIDANCE

ELECTROMAGNETIC:

RF - Microwave - Millimeter Wave - Sub MM Wave - Long Wave IR - Infrared - Visible - Ultraviolet

OTHER: Acoustic - Magnetic

ENVIRONMENT SENSING GUIDANCE

Inertial - Terrain Reference - Star Reference - Radionavigation Aid Reference - Global Positioning System

MISSIONS	APPLICATIONS	MODES	COMPONENTS	TECHNOLOGIES
Air-to-Air	Missiles	Command	Sensor	Detectors/Sources
Air-to-Surface	Projectiles	Beamrider	Seeker	VHSIC
Surface-to-Surface	Bombs	Homing	Processor	CCD
Surface-to-Air	Submunitions	Passive	Autopilot	Microprocessors
Undersurface	Mortars	Semiactive	Maneuver	Fiber Optics
	Torpedoes	Active	Fuze	SAW Devices
		Multimode	Warhead	Integrated Optics
		Inertial	Interfaces	Focal Plane Arrays
		Matcher/Correlator		Microgyros
		Multispectral		Radome/IR Domes
				Digital Technology

SIGNATURES — COUNTERMEASURES — SIMULATIONS

FIGURE 1. OVERALL SUMMARY OF PGM CHARACTERISTICS

Missiles also share in the burgeoning nomenclature: rolling airframe missile (RAM), high velocity missile (HVM), antitactical missile (ATM), anti-tactical ballistic missile (ATBM), air defense suppression missile (ADSM), antitank guided missile (ATGM), antiradiation missile (ARM), advanced medium range air-to-air missile (AMRAAM), and multiple variatons of ASMs (anti-ship and air-to-surface missiles). Added to this terminology are all of the synonyms for being a smart missile: fire and forget, brilliant, precision guided, launch and leave, terminal homing, and autonomous terminal homing. The result of all of this jargon is a very confusing panoply of overlapping military programs that leaves an image of a major duplication of effort and technology running wild. This handbook is an attempt to standardize the vocabulary of precision guided munitions and to reduce some of the confusion due to the cancerous growth in jargon.

The sections that follow outline the reasons for the development of smart weapons, provide a description of their basic operation, review the variables involved in system design, and discuss future trends. A detailed outline of the construction of the diagrams that describe specific PGM operation appears in Volume 2 of the handbook.

2. WHY SMART WEAPONS?

A smart weapon is one that can change its direction, or react, in order to hit its target, based upon information obtained during its flight. This capability of deliberately changing direction falls under the general technical area of guidance and control. Many different classes of weapons can make use of guidance and control including: missiles, projectiles, bombs, submunitions, mortars, and torpedoes, as noted in Figure 1.

As a first step towards simplifying the concept of PGMs, the term "missile" is used throughout this tutorial as a generic representative of any guided system containing a warhead or employing its kinetic energy to destroy a target. The basic intent of guidance and control in all of these applications is to provide instructions of some sort to control the missile's flight path. The whole purpose of guidance and control in a weapon is to relate the x, y, z coordinates of the missile to its launcher and to its target, such that the missile's coordinates coincide with those of its launcher at the beginning of flight and with those of its target at the end of flight. This is illustrated in Figure 2. The accuracy with which this matching of coordinates between the missile and target is accomplished at the end of flight may be stated in terms of the Circular Error Probability (CEP), the miss distance, or the probability of hit. These terms will be discussed in more detail in Section 4.

In a free flight, or unguided, system such as a rocket, projectile, mortar, or bullet, the CEP (measure of dispersion about the aim point) is a function of a number of errors at launch and during flight. These include: target location errors, aiming errors, launcher tip-off errors, ballistic errors, and atmospheric disturbance errors. Design of a system requires an error budget to determine the accumulative effect of all of these errors. The larger the error budget, the larger the CEP. Once an unguided weapon is launched, it cannot be corrected for the built-in errors. Adjustments between rounds are usually made at the launcher to correct some of the errors. Other than these adjustments, the only way to make up for the inaccuracy of a free flight system is to fire many rounds.

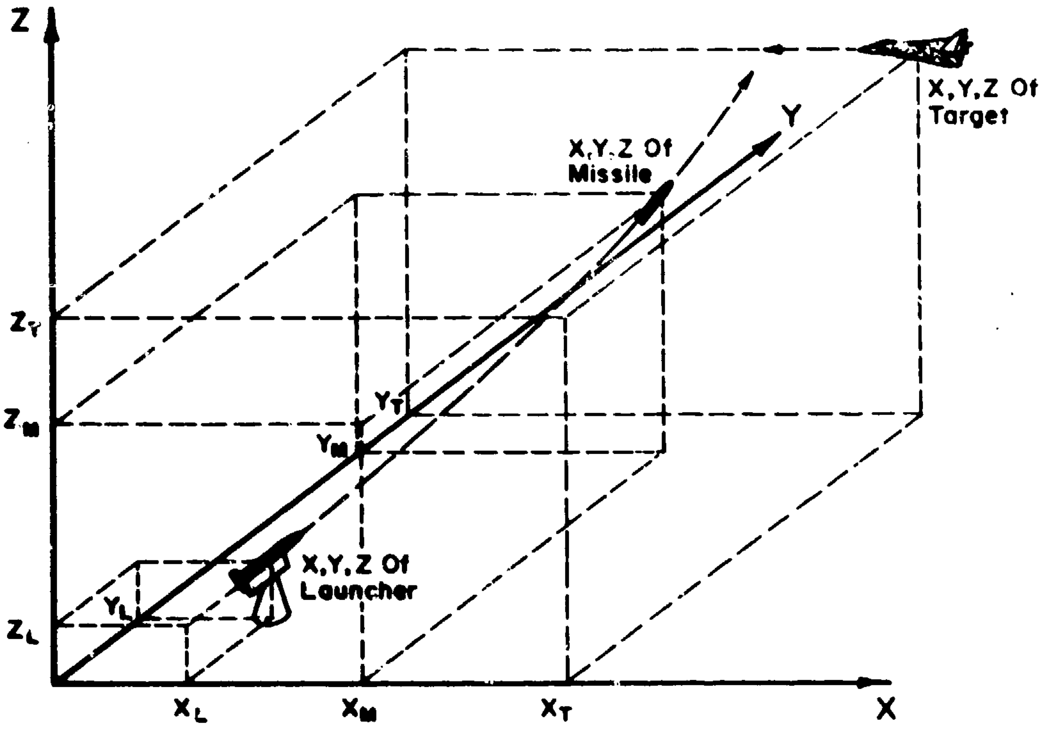


Fig. 2 X,Y,Z COORDINATES OF LAUNCHER, MISSILE AND TARGET

A guided system also has an error budget, but during flight it corrects for many of the errors experienced by an unguided weapon. Updated information on the missile's position relative to the target and/or launcher is used to reduce the CEP and to increase the probability of a kill. With increased accuracy, fewer rounds are needed to hit the target.

In general then, dumb weapons, which have a lower probability of hitting a target, must make up for their dumbness in numbers. Fewer smart weapons are needed for the same number of kills. However, smart weapons, like people, cost money to educate. A trade-off analysis must be made between numbers and cost. For example, five smart weapons costing $10,000 each may be a worthwhile investment if the alternative to kill the same target is 500 dumb weapons costing $300 each. This trade-off comparison between dumb and smart weapons was demonstrated dramatically in South Vietnam. In the case of one particular bridge, 100 sorties using thousands of pounds of dumb bombs with a

CEP of about 1000 feet could not prevent the Viet Cong from quickly repairing the relatively minor damage to the bridge. The bridge was usually back in use in a day or two. Three sorties using laser-guided bombs with a CEP of 10 to 20 feet resulted in such severe damage that use of the bridge was curtailed indefinitely.

Because fewer smart weapons are needed to kill the same number of targets that require a large number of dumb weapons to kill, fewer troops are needed to handle, supply, and use the smart weapons. In other words, a small number of troops with smart weapons can hypothetically kill as many targets as a large number of troops with dumb weapons. From a very simplistic perspective, 250 troops using 250 weapons with a p_k (kill probability) of 0.8 can kill as many targets as 1000 troops using 1000 weapons with a p_k of 0.2. On the other hand, 1000 troops with 1000 smart weapons could kill 800 targets compared to the 200 targets killed by the 1000 troops using 1000 dumb weapons. This ability of fewer troops to kill the same number of targets or the same number of troops to kill four times as many targets is called a "force-multiplier" effect. Smart weapons provide the same result with fewer people as well as with fewer weapons. There is a major potential logistics savings with either result.

Smart weapons offer so much promise that it is easy to exaggerate their potential. The argument of force-multiplier could be carried to the extreme of one soldier with several thousand weapons in a pushbutton war against a whole enemy armored division. Smart weapons are not that efficient. They are degraded by adverse weather, accuracy of target location, and countermeasures. Nevertheless, with all of these caveats, smart weapons offer a significant increase in capability. Thus, the answer to the initial question, "Why smart weapons?": To expend the least amount of resources to destroy or neutralize the enemy.

3. HOW SMART WEAPONS WORK

In order to guide a missile to impact a target, the relative positions of the target and missile must be known. Using this information, commands can be generated to cause the missile to fly on a path to intercept the target. If the position information is obtained by some means external to the missile using optical sights, radar trackers, or some other method, and commands are sent to the missile to control its course, the technique is known as command guidance. On the other hand, if the information on relative target/missile position is obtained within the missile itself using some type of seeker (radar, infrared, laser, etc.) and the guidance commands are generated internally, the technique is known as homing guidance. Inertial guidance employs a pre-programmed course based upon a known target location and very accurate measurements of missile motion using internal sensors to keep the missile on course. Inertial guidance is generally not used in PGMs except for midcourse guidance, before the terminal phase. Midcourse guidance is a term used to denote the guidance of a missile from its launch point to the vicinity of the target. It is employed in missiles that are unable to detect (see) their target when launched. The terminal phase could employ either command or homing guidance, however, terminal guidance is usually associated with homing guidance, the terms being used interchangeably by some workers in the field. Figure 3 illustrates two typical missile trajectories where the various phases of flight are denoted. In the air-to-surface scenario depicted, following launch, a midcourse guidance phase is employed to direct the missile to the target area. A search and acquisition phase is then initiated, where the missile seeker searches an area looking for a target. When a target is detected, acquisition is accomplished when the seeker locks-on to it (tracks its position). Terminal guidance is then initiated, where the seeker provides the information on the relative positions of the missile and target, which is then used to guide the missile to impact (homing guidance).

In the surface-to-surface scenario shown, a gathering phase is shown following launch, where the missile enters a wide field of view or wide beam-width of the controller. In this phase, the command system captures or gains control of the missile and directs it to the line-of-sight where a narrow

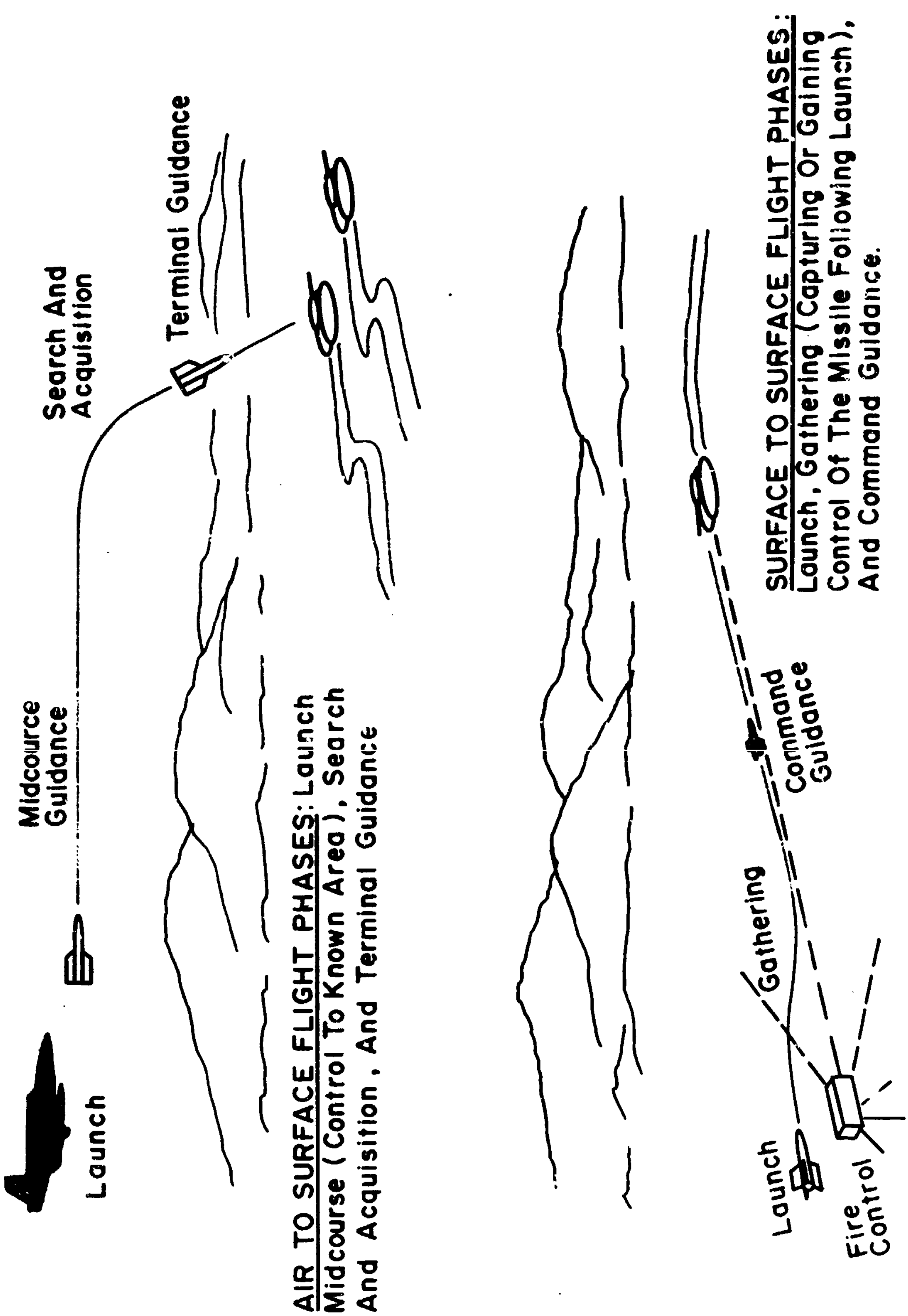


Fig. 3 TYPICAL TACTICAL MISSILE TRAJECTORIES

field of view (beamwidth) is employed to track the target. The missile is then commanded to follow this line-of-sight, causing it to hit the target. This is a form of command guidance known as command to line-of-sight (CLOS).

A number of variations of these two types of guidance have been developed over the years as shown by the diagram in Figure 4. Three of the four major types of guidance named in the figure have already been mentioned. The fourth type, beam riding, results in the same missile trajectory as CLOS guidance, but it is achieved in a slightly different manner that will be explained in subsequent paragraphs.

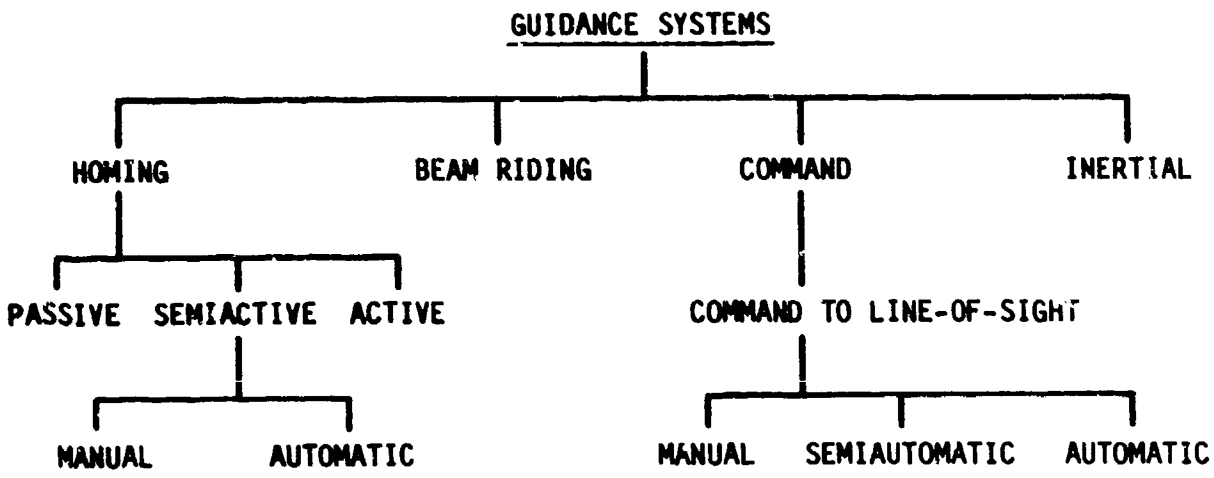


Figure 4. Types of guidance sytems.

3.1 Homing Guidance

There are many variations in the way in which homing guidance can be implemented, but one basic concept can be found in all of them; a target tracking device (called a seeker) is contained within the missile that generates the signals used to steer the missile toward the target. Because the tracker is in the missile, the positional accuracy improves as the missile gets closer to the target. This is in contrast to command systems, where positional accuracy usually deteriorates at long ranges, i.e., when the missile is approaching the target. This is especially true in long range air

defense systems where small angle tracking errors translate into significant distances at long ranges.

In describing the air-to-surface scenario of Figure 3, the search, acquisition and lock-on operations were performed by the missile. However, these can be carried out in a number of ways. The simplest is where the launch aircraft carries out the search and acquisition function and sends target position information to the missile seeker directing it to lock-on to the target before the missile is launched. This is known as lock-on before launch (LOBL). A more complex operating sequence is used when it is not possible for the missile seeker to lock-on while still on the launcher. This can be due to interference from the radar associated with the launcher, because the target cannot be tracked through the high acceleration launch phase, because the target is not within the seeker's field of view, or other reasons peculiar to the particular system. In this case, target position information may be provided to the missile to assist it in acquiring the target after launch. However, the missile must cycle through a search and acquisition phase after it is launched; therefore, this is known as lock-on after launch (LOAL). This was the type of operation discussed in Figure 2.

Terms such as 'fire and forget' and 'launch and leave' refer to the capability of a guided missile to reach its target once it is launched, without further intervention or support by the launch vehicle or operator. Such systems may be LOBL or LOAL. Current research and development efforts are being directed toward the area of autonomous acquisition, which is the most advanced form of LOAL. This type of operation is very difficult to achieve because it requires automatic search, target detection, recognition and acquisition, all without operator assistance. It is generally associated with ground targets which are difficult to detect and identify without human assistance. Such systems are attractive because they do not require the launch vehicle/operator to enter the target area where it would be subject to enemy fire. In some respects, these are the smartest of the smart weapons. They will be mentioned again after further discussion.

Referring back to Figure 4, there are three modes of homing guidance: passive, semiactive, and active. These relate to the source of energy used for target tracking.

3.1.1 Passive Guidance Mode

Passive guidance systems utilize energy emitted by the target itself for tracking or utilize energy originating from natural sources (sun, moon, stars) that is reflected from a target. They may also operate on the basis of the contrast in energy emitted between the target and its surrounding background, i.e., the target may emit less energy than the background. One of the earliest examples of this type of guidance system was the infrared (IR) tracker that sensed the infrared radiation from the jet engine of an aircraft. The SIDEWINDER missile, which is still in use, employs this technique. Other passive systems have been developed using television, which operates by using the light reflected from the target. Television seekers have been employed in both command guidance and homing systems. In homing systems, the target is selected by the operator by placing a tracking gate over it on the display. The tracking gate is an electronic circuit that generates a cursor or indicator on a display, which once positioned on a target can automatically track it and provide information on its position relative to some reference point in the scene (generally the center of the display). The television seeker then generates the proper signals for the autopilot to command the missile to hit the target. Recent efforts are being devoted to developing an infrared imaging seeker which is analogous to a television seeker except for the wavelength of the energy detected and the fact that the energy is radiated by the target, not reflected. This will allow operation at night. Radiometers have also been considered for possible use in seekers. These devices sense the low level thermal radiation emitted from all objects and may provide a means of detecting and tracking targets of interest.

Since passive guidance systems do not require further intervention from the launcher once they are locked to the target, they fall into the category of 'fire and forget' or 'launch and leave' weapons. They also have the potential for autonomous acquisition. Figure 5 illustrates the concept of passive homing guidance, where an infrared seeker receives the radiation from the hot exhaust plume and processes this signal to provide missile guidance.

Although passive in operation, antiradiation missiles (ARM) home on the microwave energy transmitted by target radars. However, they employ receivers more like those used in the systems described below than the true passive type

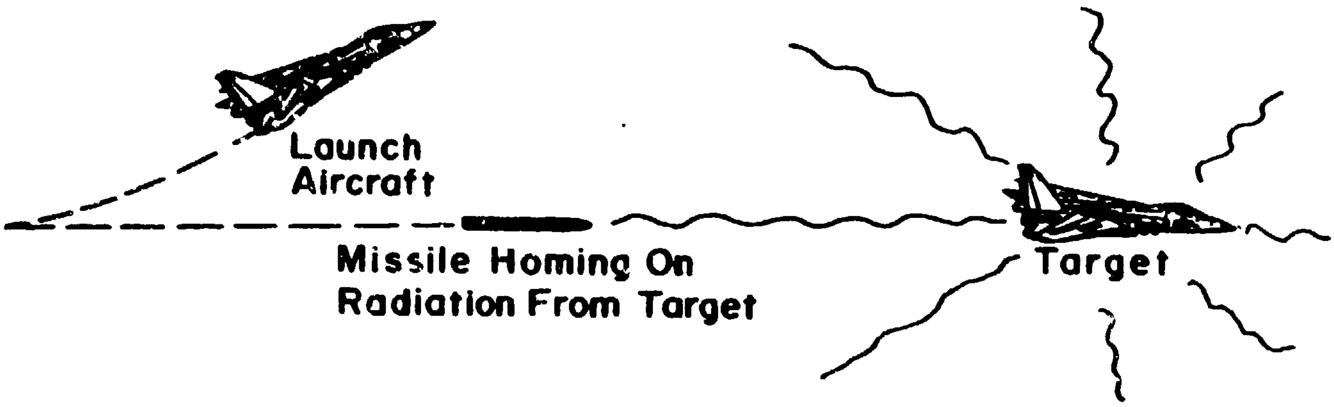


Fig. 5 PASSIVE HOMING GUIDANCE
(Air-to-air case)

systems which generally depend upon thermal radiation or reflected light. SHRIKE, HARM, and ARP (Anti-Radiation Projectile) are examples of anti-radiation missiles/ projectiles that have been produced, are in development, or have been investigated.

3.1.2 Semiactive Guidance Mode

In some situations, the energy emitted by the target is not strong enough to provide a homing signal. The early SIDEWINDER missiles could only be fired toward the rear aspect of an enemy aircraft, with very limited capability from the forward aspect. Its operation was also severly degraded by clouds, reflection of the sun, and weather (rain and snow). Such limitations, as well as the requirement for long range systems, led to the development of the semiactive mode of homing. Here the target is intentionally illuminated by a beam of energy that is reflected by the target to provide a source strong enough to be tracked by a seeker located in a missile. Initially, these were radar systems, where the illuminator beam was slaved to a tracking radar to maintain continuous target illumination. In some cases, the illumination signal was injected into the tracking radar's antenna to reduce the need for a second antenna. This technique is still employed in air-to-air systems using

a continuous wave illumination signal for missile guidance. In other cases, the tracking radar signal itself is used for missile guidance. There are a number of variations of this technique employed, all for use against air targets.

Figure 6 illustrates semiactive homing guidance employing a radar seeker. The radar illumination signal is depicted by the solid arcs emanating from the launch aircraft to illuminate the target. The signal is confined to an angular volume by the radar antenna beamwidth. These signal are also received by an antenna in the rear of the missile to serve as a reference. They are reflected in all directions by the target, with only those reflected in the general direction of the missile and launch aircraft being shown by the dashed arcs in the figure. The missile seeker processes these reflected signals to guide the missile to intercept the target. The reflected signals are also recieved by the radar in the launch aircraft and are used to keep the illuminator pointed at the target (track the target).

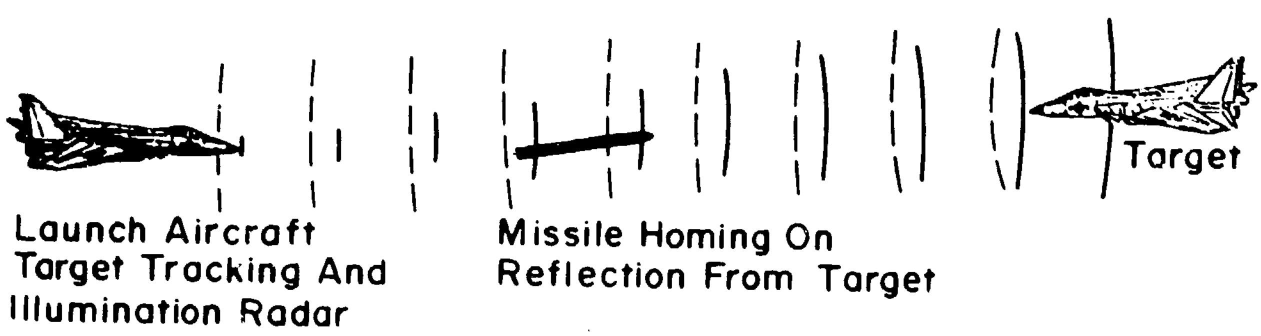


Fig.6 SEMIACTIVE HOMING GUIDANCE
(Air-to-air case)

Semiactive systems using radar have been designed to operate against air targets because of the limited target discrimination capability of the broad beamwidth of the tracking radar and illuminator. The fact that an aircraft presents a well-defined object in space allows it to be illuminated with essentially no nearby clutter to detract or interfere with the terminal homing seeker. Aircraft flying in formation can present a problem, but the terminal homing receiver tends to resolve and select a single target as the range closes.

With continued technological development, the beamwidth of illumination sources has become smaller through the use of energy of shorter wavelengths in the millimeter wave and optical spectrum. It became possible to illuminate an area that was less than the size of a target, eliminating reflections from the surrounding area. The laser provided this capability, which led to the development of air-to-surface and surface-to-surface semiactive terminal homing systems for use against tactical targets. The term "precision guided munitions" was coined as a result of the development of such systems. Rather than calling these laser devices "illuminators", as in the radar case, they became known as "designators", because their angle resolution is high enough to designate a specific target. They serve the same function as the radar illuminator, but in a slightly different manner. Because of their very small beamwidth they are difficult to employ against a maneuvering target, such as an airplane. They are commonly aimed at the target by a human operator using some type of optical sight or imaging system, and therefore, are usually employed against stationary or slowly moving targets at fairly short ranges. By using an operator to aim the designator, these systems are much lower in cost than if they were slaved to an automatic tracking system, and thus they have been adapted to a wide variety of guided weapons including bombs, guided projectiles, and guided missiles.

Weapons employing semiactive laser seekers may be launched from a position near the laser designator or from a remote location. The seeker may be locked on before launch if launched from a position near the designator. It must go through a search and acquisition phase and lock-on after launch if coming from a remote location. The laser designator signals may be coded so that a given missile will only track its intended target, allowing multiple designators to be used in an area containing many targets.

Figure 7 illustrates one type of semiactive laser guidance employing a ground based laser designator and a remotely launched missile containing a laser seeker. The designator beam is very narrow as illustrated by the small arc extending from the designator to the target. The designator is pointed at the target by an operator using an optical sighting device. The laser energy is scattered in all direction by the target, due to its surface roughness, as denoted by the dashed arcs emanating from the target. This reflected signal is received by the laser seeker in the nose of the incoming missile and is processed to provide guidance commands to guide the missile to impact the target (the source of the reflection).

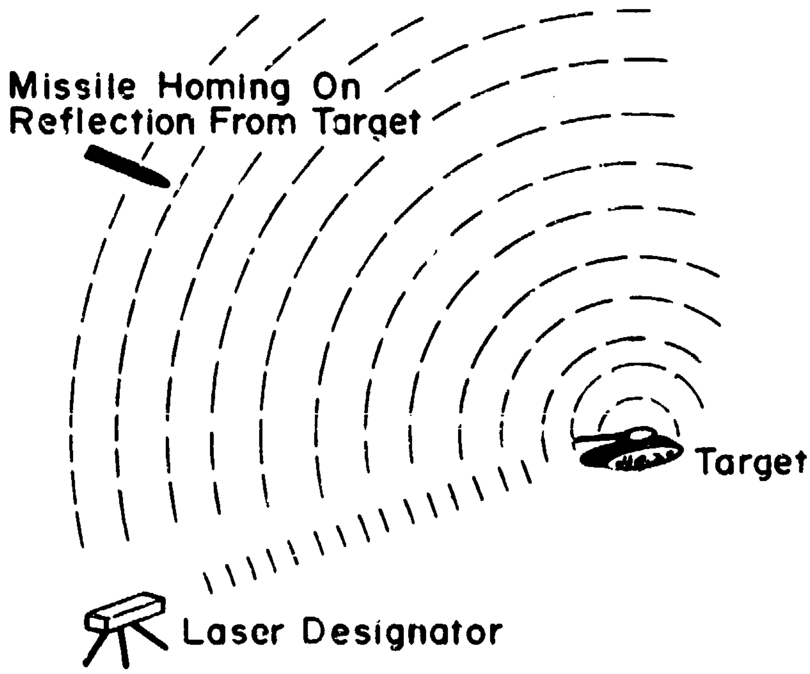


Fig. 7 SEMIACTIVE LASER GUIDANCE
(Air-to-surface case)

Semiactive systems do not qualify as fire and forget or launch and leave weapons. The illuminator or designator must be pointed at the target to provide the homing signal throughout the missile's flight. Although an aircraft may leave the area immediately after launching missiles or bombs that are intended to home on the reflection from a laser designator aimed by a forward observer on the ground, this is not what is generally meant by launch and leave, since someone is providing assistance to the guided missile throughout its flight.

To insure successful operation of a semiactive system, the target must be illuminated during the entire guided missile flight. This ties up the illuminator/designator for this period of time and restricts the rate of fire to a single engagement at any one time. To solve this problem in situations where multiple simultaneous target engagements are required, active homing guidance systems were developed.

3.1.3 Active Guidance Mode

Historically, attempts were made to develop active radar seekers before semiactive seekers. Because of technological problems, these systems were not successful and efforts were directed toward perfecting the semiactive systems. As progress was made in component development, active systems became feasible and have been produced. In these systems, the guided weapon carries the target illuminator/designator and becomes a self-contained guidance system in the same sense as a passive system. Active systems usually employ radar seekers because of their ability to automatically track a target and thereby control the illuminator. However, the range of such systems is usually quite limited because of the restricted power, size, and weight requirements, and they are fairly complex due to the technical problems associated with locating a transmitter and sensitive receiver within the confined space available in a missile. In fact, active guidance has normally been reserved for the final terminal phase of an attack, with some type of midcourse guidance employed to direct the missile to the vicinity of the target. With the recent interest in launch and leave or fire and forget weapon delivery, increased emphasis is being placed on active guidance systems, generally in the air defense or air superiority role, where the target is of high enough value to warrant an expensive missile. Efforts are also underway to employ active radar guidance in the air-to-surface role using millimeter waves, where the radar beamwidth can be made narrow. The problem is one of target recognition and discrimination, because fairly large signals are received due to reflections from various objects and the ground surrounding the target. Various electronic techniques are being pursued to try to find ways of recognizing the target and separating the target return from that of the clutter.

Active radar homing guidance is illustrated in Figure 8. Here the solid arcs emanating from the missile represent the signal transmitted by the radar in the missile. The arcs also represent the beamwidth of the missile radar

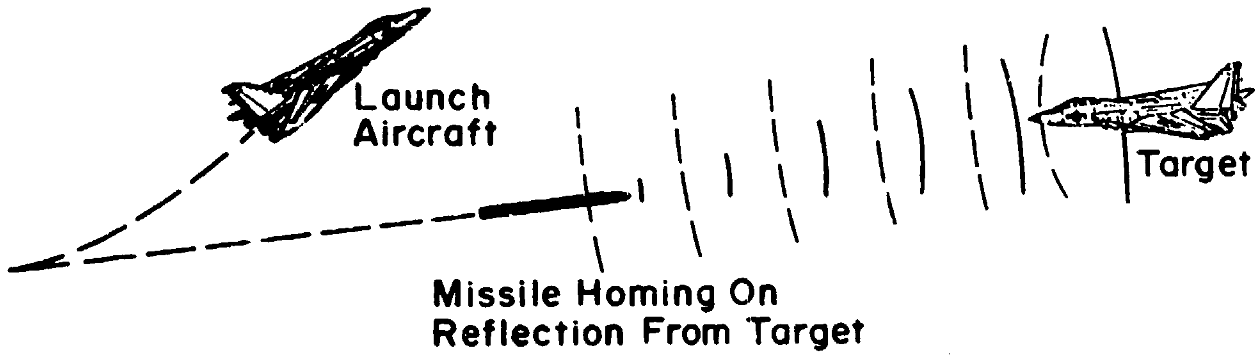


Fig. 8 ACTIVE HOMING GUIDANCE
(Air - to - air case)

antenna, shown as being much broader than the beamwidth of the aircraft radar antenna shown in Figure 5. This is usually the case because of the limited space available in a missile, dictating a smaller antenna. However, narrow beamwidths can be attained by using higher frequencies.

The radar signal is reflected in all directions by the target. Only the energy reflected in the direction of the missile is shown by the dashed arcs in Figure 8. This is not intended to imply that the signal reflected back toward the missile radar is greater than that reflected in other directions, but is for illustration only. The magnitude of the reflected signal and its apparent source varies with the aspect from which the target is viewed. Due to the target's motion, the viewing aspect is constantly changing, giving rise to both amplitude variations (scintillation) and angular variations (glint) in the signal received by the missile, i.e., the target echo. This holds true for all radar systems including the semiactive system discussed above.

The missile radar processes the received target echo and generates guidance commands to the missile to intercept the target. As shown, the active guidance system frees the launch aircraft once it is activated.

3.2 Beam Riding Guidance

In beam riding guidance a sensor is placed within the missile to generate internal signals to keep the missile within a beam (radar or laser) that is pointed at the target, usually by a subsystem at the launcher. In this way it follows the beam (rides the beam) to the target. Various methods of coding

the beam have been developed so that the sensor in the missile knows where it is with respect to the center of the beam. This sensor generates the proper commands to keep the missile near the center of the beam as it flies toward the target. The beam that is used to direct the missile to the target may also be used for automatically tracking the target (as in a tracking radar) or it may be directed to point at the target by some other means. Figure 9 illustrates radar beam riding guidance, where the illumination and target tracking radars are shown as a single unit. The solid arcs denote the transmitted signal, which the missile receives and uses for guidance. The dashed arcs shown represent the target reflection in the direction of the radar. This echo signal is received by the radar and processed to keep the radar beam pointed at the target.

The missile receiver (sensor) antenna must have a fairly wide beamwidth in the rear aspect, to insure that the signal can be received as the missile turns. This is because for certain intercept geometries, especially high speed crossing targets, the missile will develop a fairly high velocity component perpendicular to the beam's center, i.e., in order to keep up with the beam's angular motion as it tracks the target.

Figure 10 illustrates the type of missile trajectory that is generated by a beam rider guidance system. The relative positions of the target and missile are shown at various instants of time, the missile always being in the beam that tracks the target. The shape of an actual trajectory will depend upon the velocities of the target and the missile during the engagement. This figure shows that the missile does not simply fly up the beam, but as stated, must develop velocity perpendicular to the beam (turn) in order to intercept a fast moving target. The need for a broad beam rear antenna can be seen by the angle between the tracking beam and the missile axis.

In contrast to homing guidance, a beam rider does not require a seeker in the front of the missile and therefore the nose can be shaped to minimize aerodynamic drag. On the other hand, angle tracking errors in the guidance beam translate into position errors that are directly proportional to the range between the target tracker and the target. For accurate guidance at long ranges, a very good target tracking system is required, having small angle tracking errors.

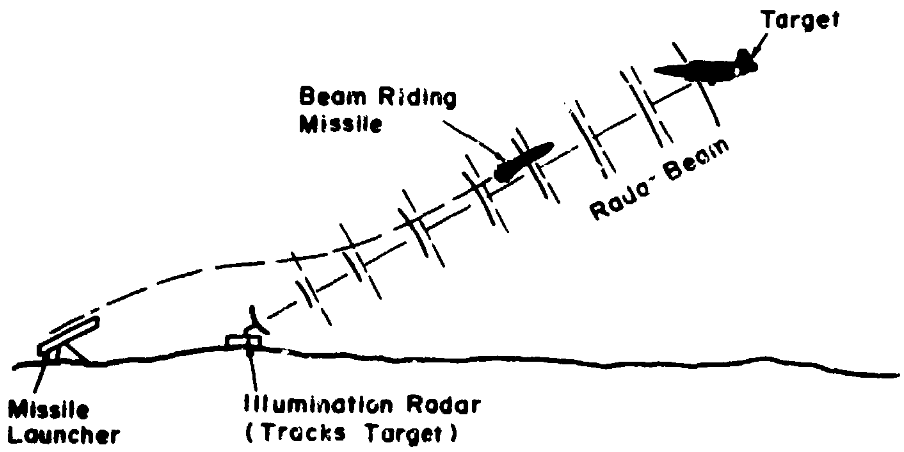


Fig. 9 BEAM RIDING GUIDANCE

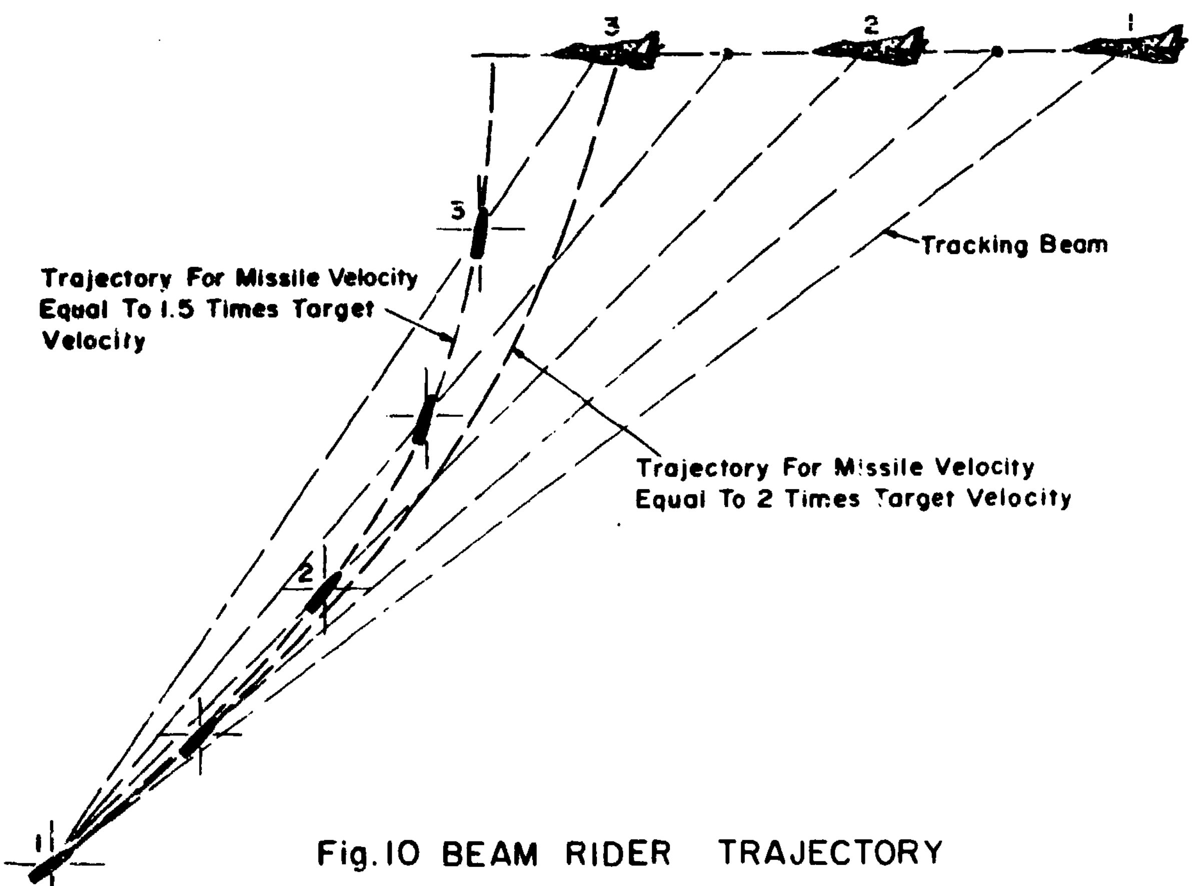


Fig.10 BEAM RIDER TRAJECTORY

3.3 Command Guidance

As stated earlier, command guidance is based upon observing the target and missile positions and velocities, and sending commands to the missile to adjust its flight in order to intercept the target at some predicted position. The accuracy of command guidance suffers at long ranges because angular pointing errors in the trackers translate into position errors that are directly proportional to range. Therefore, the target and missile position errors become greater as the distance from the tracking equipment that generates the commands increases. There are exceptions to this in systems where the missile carries the target sensor, such as a television camera. Here, the television signals are sent back to the operator who controls the missile through some type of data link. Radio links have been used in the past, but fiber optics may be used in the future with the optical fiber uncoiling from the missile as it flies. The fiber optics concept limits the maximum missile range because of the limited amount of cable that can be carried. In either case, here the resolution improves as the missile approaches the target, decreasing the errors in sensing the relative position of the target with respect to the missile. The WALLEYE air-to-surface missile and GBU-15 glide bomb employed TV systems to improve command guidance accuracy.

Commands may be sent to the missile by radio frequency data link, via the radar or laser beam used to track the missile, or over very thin hairlike wires that uncoil from the missile as it flies.

A radar command link is employed in the PATRIOT system, where a semi-active radar target tracker is located in the missile that relays all of its signals to the ground for processing by a powerful computer. This is known as TVM, tracking via the missile, and is employed to get around the accuracy problem mentioned above. Commands are generated by the computer and sent back to the missile for both guidance and to control the radar target tracker. This data link must be very secure to prevent jamming or interference from affecting the system's operation. Wire command links are employed mainly with antitank missiles having a relatively short range. Radar command guidance was used in the NIKE air defense system deployed throughout the U.S. in the 1950's where each site had a number of radars to track the target and missile. Commands were sent to the missiles via the missile tracking radar.

Figure 11 depicts generic command guidance based upon separate target and missile tracking radars, with the command link included in the missile tracking radar. As in previous figures, the solid arcs emanating from the tracking radars represent the transmitted radar signals. These signals are reflected by the target in all directs, the dashed arcs representing the reflection in the direction of the target tracking radar. This reflected signal is processed by the target tracking radar to determine the target's range and angle and the information is fed into the guidance computer. The missile carries a beacon, or radar transmitter, which is triggered by the signal received from the missile tracking radar. The beacon transmits a strong signal back to the missile tracking radar, shown by the solid arcs emanating from the missile. This insures accurate tracking of the missile and can also provide a data link from the missile to the ground. The missile's range and angle is also fed into the computer. The computer then calculates the trajectory the missile should fly in order to intercept the target and generates commands which are sent to the missile via the command link. This link is shown by the jagged line between the missile tracking radar and the missile. By monitoring the target and missile positions and refining the trajectory calculations throughout the engagement, the missile is guided to intercept the target.

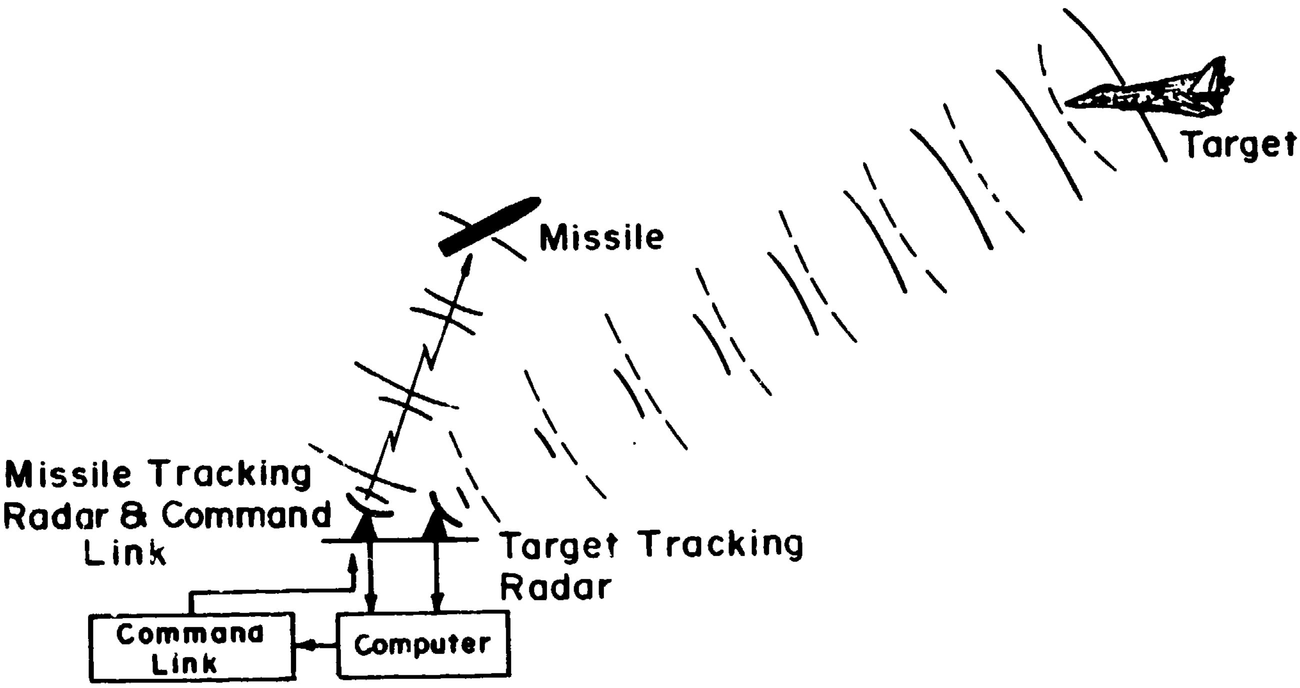


Fig. 11 GENERIC COMMAND GUIDANCE
(Surface-to-air case)

A more modern implementation of radar command guidance is shown in Figure 12, where the operation of a track-while-scan radar is depicted. Two fan shaped beams are scanned at right angles to each other to obtain elevation and azimuth angles and the range of both the target and the missile. A computer then calculates the trajectory the missile should fly in order to intercept the target, and commands are sent to the missile via a command link to control the missile. For successful operation, the missile must remain in the volume scanned by the two tracking beams.

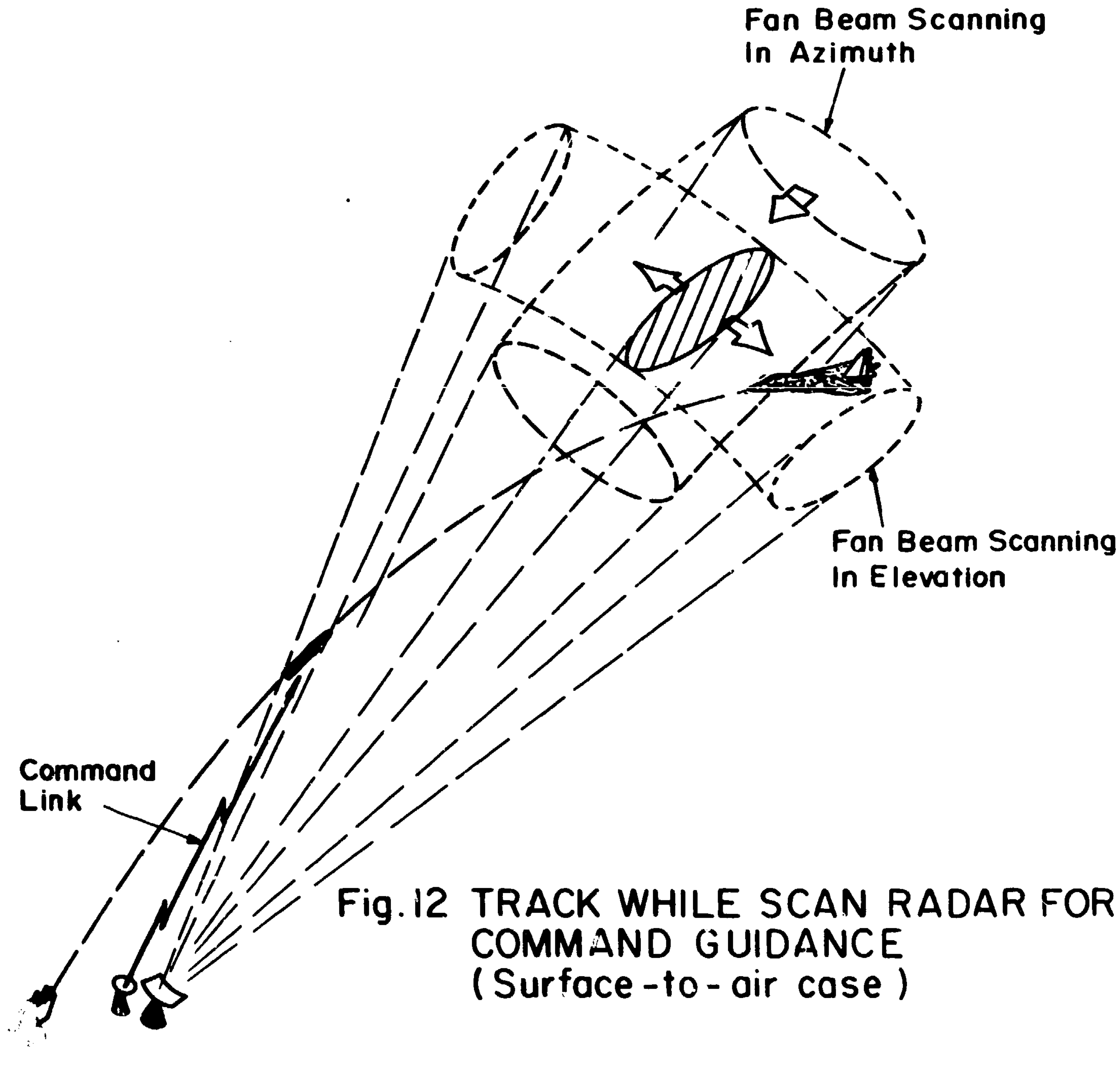


Fig. 12 TRACK WHILE SCAN RADAR FOR COMMAND GUIDANCE (Surface-to-air case)

A derivative of the command guidance technique is known as Command to Line-of-Sight (CLOS) or Line-of-Sight (LOS) guidance. It is sometimes known as three point guidance, the three points being the tracker, missile and target. If the missile can be made to stay on a straight line between the tracker and the target, i.e., the line-of-sight, it will hit the target. The target is tracked with an optical sight by an operator, by a tracking or track-while-scan radar, or through some other means. This tracking process establishes the line-of-sight from the tracker to the target. In manual systems, the operator tracks the target and controls the missile to follow the line-of-sight. This is quite a work load and is usually reserved for low cost anti-tank missiles where the target is not moving rapidly. Semiautomatic systems require the operator to track the target, but missile tracking and control is done automatically. The missile usually carries a radar beacon, flare, or a light to provide a strong signal to the missile tracker. The launcher/tracker calculates the corrections necessary to keep the missile on the LOS and sends these commands to the missile. In automatic systems, both the target and the missile are tracked automatically and a computer generates the commands sent to the missile.

With the semiautomatic and automatic systems, the target and missile may be tracked using two separate apertures (optical or radar) or by a single aperture. When using a single aperture, the system is known as a differential tracker and is used to eliminate the problem of errors in boresighting of the two apertures, the errors in both target and missile tracking of the two apertures, and the need for two different trackers. Differential tracking is accomplished by multiple beam forming, track-while-scan systems, or multiplexing.

A number of air defense and antitank missile systems employ the CLOS guidance technique with numerous variation in implementation. The trajectory of a CLOS and a beam rider missile are similar, since they both follow the line-of-sight from launch to impact.

3.4 Inertial Guidance/Midcourse Guidance

In tactical weapon systems, inertial guidance is usually associated with midcourse guidance; that phase of flight employed by some guided missiles between launch and the search/acquisition phase prior to terminal homing. Inertial guidance requires an inertial measurement unit (IMU) or portions

thereof, to sense missile motion and to generate guidance signals to control the missile to fly to a preselected position. An IMU is composed of a triad of gyroscopes and accelerometers that measure the turning rate and acceleration of the missile. A triad consists of three devices mounted to sense rotation or acceleration in three orthogonal planes. Through proper processing of this data, the position of the missile with respect to the launch point can be computed.

The classic approach to IMU design is to mount the accelerometer triad (measures acceleration in up-down, right-left, and front-back directions) on a platform that is space stabilized by a triad of gyroscopes to maintain the platform stable in pitch, yaw, and roll planes. In other words, this platform maintains its orientation regardless of the missile's motions. By integrating the accelerometers' outputs, the distance and direction traveled by the missile can be computed. The current trend is toward strapdown systems, where the inertial components are mounted to the missile body rather than on a stable platform. With this arrangement a computer is needed to calculate the same information because the accelerations measured are not along fixed directions. In both approaches, a navigation computer is required to convert the calculated position information into commands to control the missile.

The accuracy of an inertial guidance system is usually given in terms of drift rate. For most tactical systems, the time of flight is usually fairly short, therefore, low accuracy inertial components may provide satisfactory performance. Where longer flight times are required, the missile's position may be updated by using some other type of position fixing technique. Position updating may be accomplished by using satellite data from the Global Positioning System; landmarks sensed by either radar, IR, or electro-optical devices and used for area correlation; through terrain profile data correlated with stored data, as in cruise missiles (TERCOM); or through some other technique.

Inertial navigation is used in intercontinental ballistic missiles, where the target location is known and the launch position is known. The navigation systems used in these missiles are very accurate and quite expensive. Such systems are also used on long range aircraft, ships and submarines.

3.5 Multimode Guidance

By combining two or more guidance modes into a single missile, a multimode guidance system is obtained. It is common to include a midcourse and homing guidance system in a single missile, and recent efforts are aimed at employing multimode systems that employ more than one mode of guidance in the terminal phase. These systems are intended to defeat enemy countermeasures, provide higher accuracy, reduce false alarms, or improve target detectability as compared to a single mode system. This term is sometimes erroneously employed to denote systems that utilize more than one portion of the electromagnetic spectrum for their operation. For example, a system may use both active millimeter waves and passive infrared, which is both multimode (active and passive) and multispectral (MMW and IR). The onboard electronics and processing requirements go up in complexity and cost with multimode systems because of the additional sensor and signal processing requirements.

3.6 Multispectral Guidance

Multispectral guidance employs two or more wavelengths for target sensing and/or tracking. Examples of multispectral guidance are the use of two-color infrared, dual frequency RF, infrared and RF, or infrared and ultraviolet as in the STINGER-POST air defense missile. As already stated, the reason for using two frequencies/wavelengths is to reduce the effect of countermeasures, increase accuracy, improve target detectability, and decrease false alarms. Multispectral techniques can be difficult to implement due to the complexity in selecting and handing over from one sensor to another as the target is approached.

3.7 Major PGM Subsystems

The component parts of a smart weapon are indicated in block diagram form in Figure 13, for a homing guidance system. This diagram essentially duplicates the components block in Figure 1: sensor, seeker, processor, autopilot, maneuver, fuze, warhead, and interfaces. Each of these components of a PGM will be discussed briefly in the following subsections. All of these components may not be included in every PGM, although they are usually found somewhere in the total weapon system.

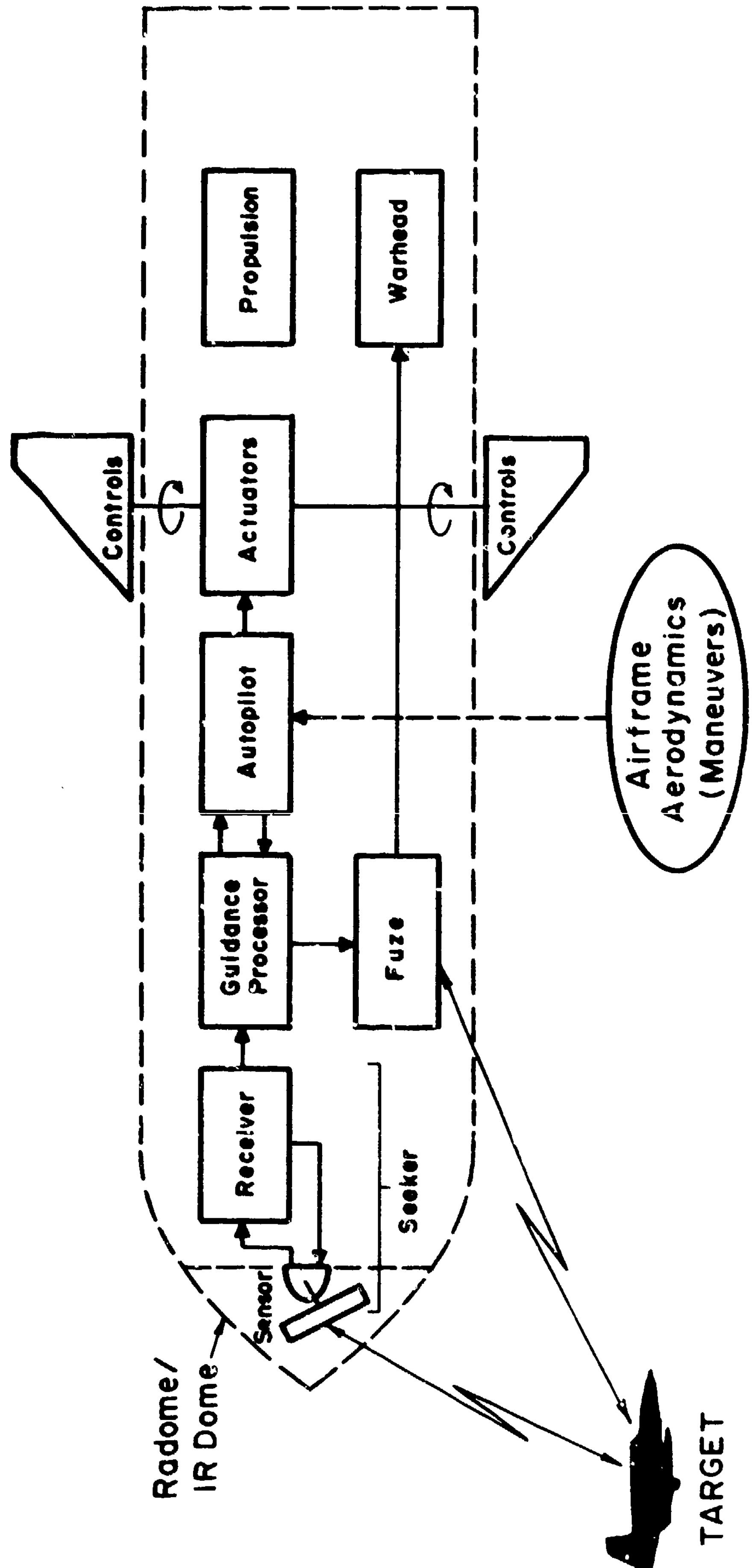


Fig. 13 BLOCK DIAGRAM OF COMPONENTS OF A GUIDED MISSILE

3.7.1 Sensor

The sensor is the receiver of any signals which come from outside the PGM that are used to direct its course. Like the human eye or ear, the sensor is the interface to the outside world. The sensor is the basic building block around which the whole PGM is built. The choice of sensor ultimately defines the uniqueness of the individual PGM. The sensor's signal may come from any of three sources: energy reflected from the target, energy emitted from the target, and/or energy from the target's immediate environment. These options will be considered in more detail later. For the moment, assume that the sensor is selected to recognize hot targets, targets which emit infrared energy. In this case, the sensor will be selected based upon a particular frequency or frequency band emitted by the target and will be optimized to respond to the given target signature. The design of all smart weapons depends upon this optimization, since the sensor is the key to PGM operation. Blind or confuse a PGM's sensor and the PGM is no longer smart. But a PGM is not just a sensor; there are other vital components.

3.7.2 Seeker

The next level of integration in a PGM is to put the sensor in a seeker. The seeker takes the sensor data and processes it for use by the PGM. The seeker also serves the function of making sure that the sensor receives the maximum amount of target information. Its very name, seeker, designates its function. It orients the sensor to survey, acquire, and finally to lock-on and track the target. Major components comprising the seeker include the following:

- energy-gathering system; i.e., antenna for radio frequency or lense/mirror for infrared, visible, and ultraviolet spectral regions, including radome or IR-dome/window,
- stable platform and its associated control system, (body fixed seekers employ inertial sensors for an equivalent function),
- sensor to convert the received energy into a more usable signal for processing,
- signal processing system used to produce a signal to point the antenna/mirror at the target and/or to provide signals to ultimately control the missile's trajectory.

Figure 14 contains a cutaway drawing of a typical radar seeker illustrating the placement of various components.

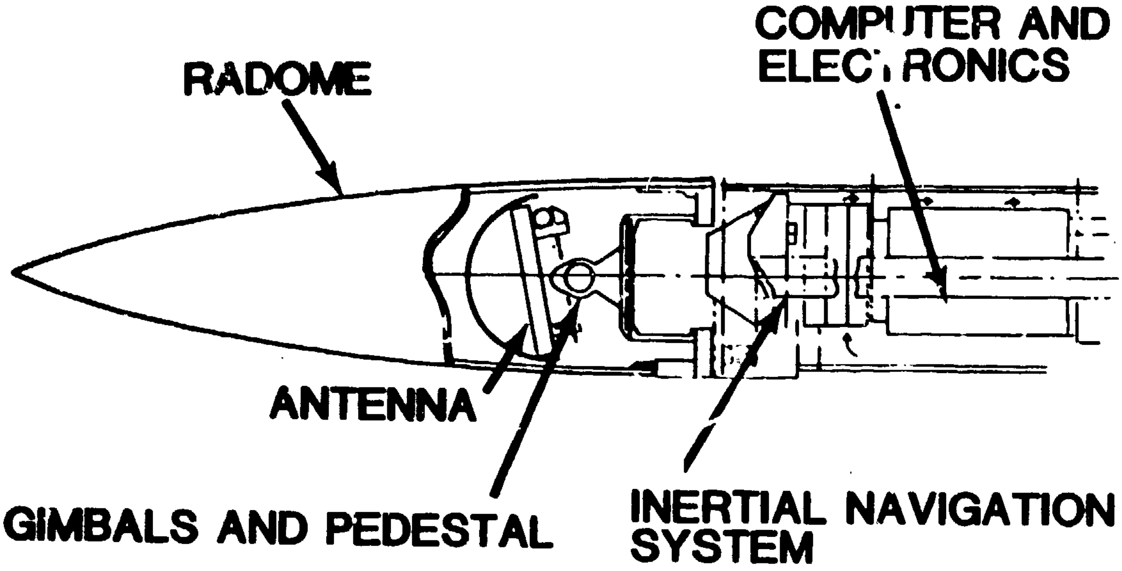


Fig. 14 DRAWING OF TYPICAL RADAR SEEKER

The antenna/mirror is designed to have a directivity and associated angular beamwidth (or field of view) within which it gathers the most energy. This may be likened to the light beam produced by a flashlight. This characteristic is used to sense the direction to the target, generally expressed as the line-of-sight (LOS). The seeker processes input data to maintain the target in the beamwidth as the missile flies, and in this manner measures either the angle or the change in the angle of the line-of-sight as the missile tracks the target. However, as the missile flies, it is buffeted by the air and pitches and yaws. If the antenna/mirror is fixed to the missile body, these motions will be added directly to those produced by the changing positions of the missile and target, which are the ones of prime importance to the guidance system. To avoid this contamination in the measurement of the angle or angular rate of the LOS, the antenna/mirror is usually mounted on a gimbaled stable platform that provides an inertial reference for making angular measurements. Stable platforms based upon rotating mass systems (gyroscopes) integral with the antenna/mirror or upon smaller gyroscopes mounted on the platform with appropriate feedback control systems have been employed. In this manner, rapid missile motions due to flight instabilities are removed, and the tracking device (seeker) only has to measure the slowly changing angle

between the missile and target due to the closing motion and intentional maneuvers.

Systems have been developed that employ antennas fixed to the missile body, i.e., body fixed seekers. The TALOS, a long range surface-to-air missile used this techniques. By mounting four interferometer rod antennas around the nose of the missile, the center could be used for a ramjet intake. To achieve high accuracy with this approach, ancillary inertial components are placed in the missile to provide the information required to decouple the body motion from the antenna to obtain the basic information required for guidance; i.e., the angular rate of the line-of-sight (LOS). This requires clever design to avoid guidance instability in case of target signal fading, and is not simply a matter of subtracting the signals generated by the body motion from that generated by the target tracker.

Some concepts currently being explored employ fixed sensors to determine target direction as a means for triggering a warhead. These are known as sensor fuzed munitions, and do not always contain a seeker, per se. Upon detection of a target, a signal processor triggers a directional warhead, through appropriate logic, so as to hit the target detected. These systems will be included in the broad category of PGMs.

The terms "antenna gain" and "antenna beamwidth" are commonly used when referring to radar seekers, and the following discussion may assist the reader in better understanding their meaning. An isotropic antenna (theoretical antenna) radiates electromagnetic power equally in all directions and is said to have an antenna gain of one (1). The antenna gain pattern may be thought of as a spherical surface having uniform power density (power per unit area) over the entire surface area. The power density multiplied by the surface area will equal the total power radiated. If the antenna is designed to concentrate its power into a small area (at the expense of other areas), the antenna is said to be directive, and have a gain in the direction of power concentration. For example, if all the power is radiated to produce a uniform power density over a hemispherical surface and zero elsewhere, the antenna pattern will be a hemisphere and the antenna gain will be two (2). By increasing the concentration (making the beamwidth smaller) so that all the power is radiated through a quarter of the spherical surface, the power density is increased to four times what it was in the isotropic case, and the

antenna has a gain of four (4). Thus, it can be seen that the antenna gain is related to the increase in power density as the area over which the power is radiated (the beamwidth) changes. By decreasing this area, i.e., making the antenna more directive, the gain increases. Ideally, the power density multiplied by the surface area of the sphere cut by the antenna beam is constant, and equal to the total power radiated. In reality, due to physical constraints, small amounts of power are radiated in unwanted directions, forming what are known as sidelobes and backlobes. Antenna gains on the order of 100 to 1,000 are common in missile seekers. Sidelobes are usually 100 to 1,000 times lower than the main beam gain. Antenna radiation patterns are a means for defining the gain of an antenna as a function of direction, usually with respect to the main beam peak gain. These same concepts apply to both transmitting and receiving antennas. Antenna gain is usually expressed in decibels (dB). Figure 15 illustrates two ways of plotting antenna gain patterns. In Figure 15a, the plot is in rectangular coordinates, showing the patterns of both an isotropic and a directive antenna. The pattern gives the gain as a function of azimuth angle. The gain of the isotropic antenna is shown to be unity at all angles. The gain of the directive antenna has a peak (the main beam) and a series of sidelobes. The amplitude and distribution of the sidelobes are dependent upon the antenna design.

Figure 15b shows the same patterns plotted in circular coordinates. It may be easier to visualize the pattern when plotted in this form, however, much detail is lost near the center because of the convergence of the radial lines.

3.7.3 Guidance Processor

The guidance processor is what really gives the PGM its smarts. All smart missiles currently being developed have an imbedded processor to make the whole system follow a particular algorithm. If the retina of the eye is the sensor and the pupil, cornea, lens, eye muscles, and movable head make up the seeker, the human brain is the processor. All control of the system falls on the processor. Signals generated by the sensor are processed for target information. If the signals do not contain what the processor is designed to call a target, the seeker is commanded by the processor to continue its prearranged surveillance pattern. When a signal is received that represents a target signature, the processor makes this decision. The seeker is then

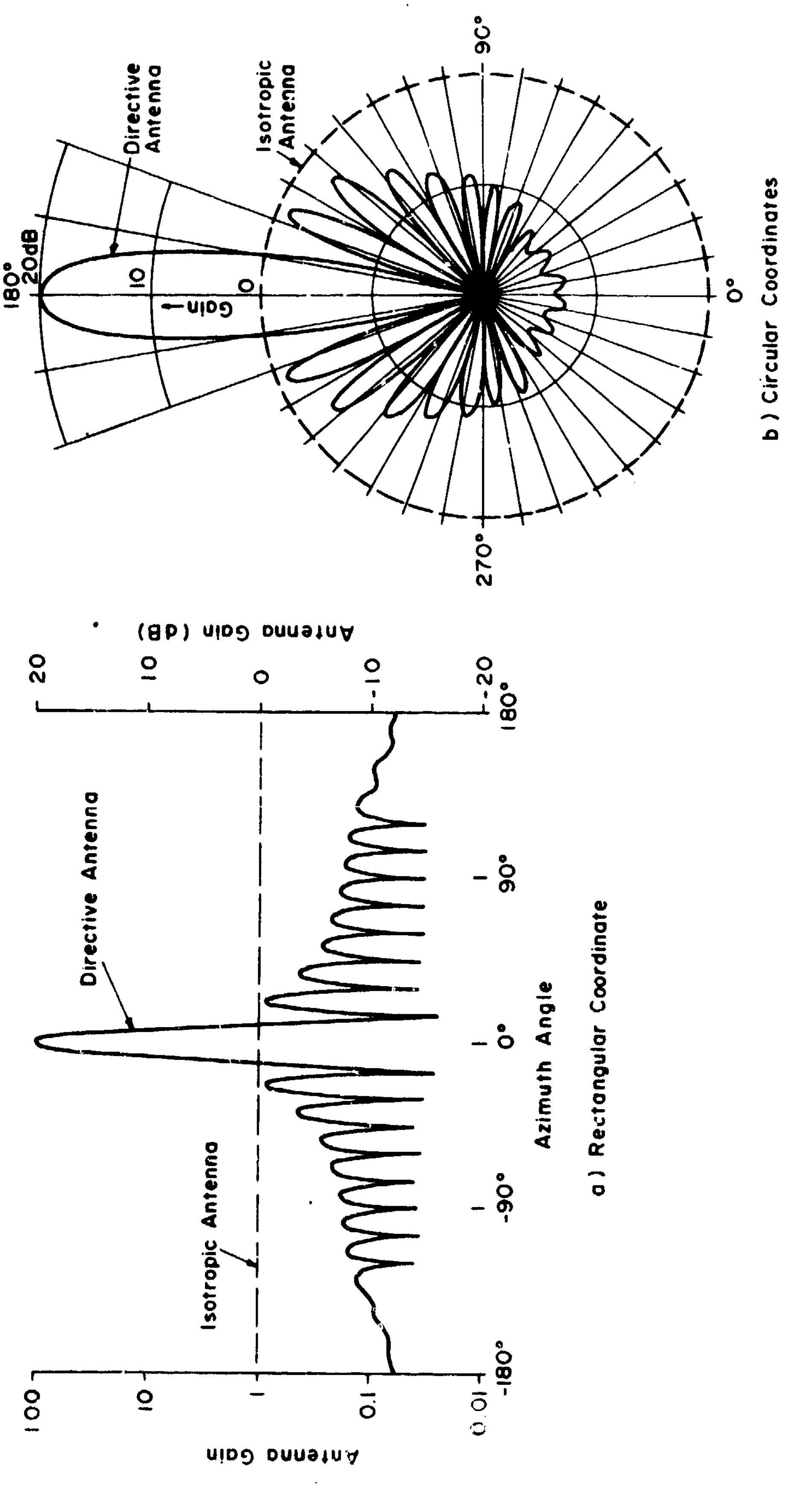


Fig. 15 ANTENNA PATTERNS

commanded to acquire the target, lock-on it, and track it. In the case of antonomous acquisition, the processor is the key; that is, the detection and recognition of targets with military value without human intervention.

The main function of the processor, after lock-on occurs, is to relate the coordinates of the missile with the coordinates of the target and to issue commands to missile components to eventually make the coordinates match. It contains the guidance laws used to direct the missile on the best course to intercept the target. In other words, the processor commands the missile to hit the target. In order to accomplish this objective, the processor is actually an intermediary between a data source and the missile control. The data source is the seeker which provides information on the target location. The missile control is the autopilot which tells the missile how to get to the target.

3.7.4 Autopilot

The autopilot translates the commands produced by the guidance processor into a form suitable for properly driving the control actuators while maintaining flight stability and airframe integrity. The design of the autopilot is highly dependent upon the aerodynamics of the missile airframe and the type of controls employed. In general these controls are of an aerodynamic nature, and their performance characteristics provide the basis for the autopilot design. Because some guided missiles must perform over extreme ranges of the flight region, the autopilot may be designed to compensate for some of the nonlinearities in the aerodynamics and provide a stable system.

Autopilots may be configured as open-loop or closed-loop systems. In an open-loop system, missile motion is produced solely on the basis of the seeker's commands. Such an autopilot finds application in simple guidance systems where small size and low cost are important considerations. Antitank missiles and submunitions are typical candidates for open-loop autopilots, although the early SIDEWINDER, an air-to-air missile, used such a design. The closed-loop system employs inertial sensors to form a feedback signal to stabilize the missile or to make the overall aerodynamic gain independent of altitude and velocity. This type of system can provide stabilization of the missile airframe in pitch, yaw, and roll (See Figure 16) similar to the autopilot commonly associated with aircraft.

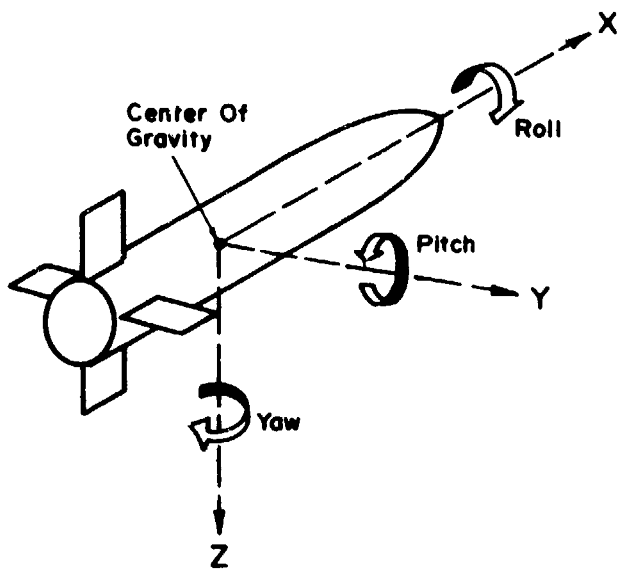
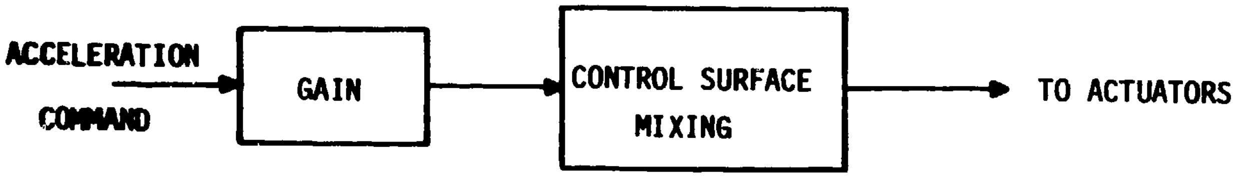


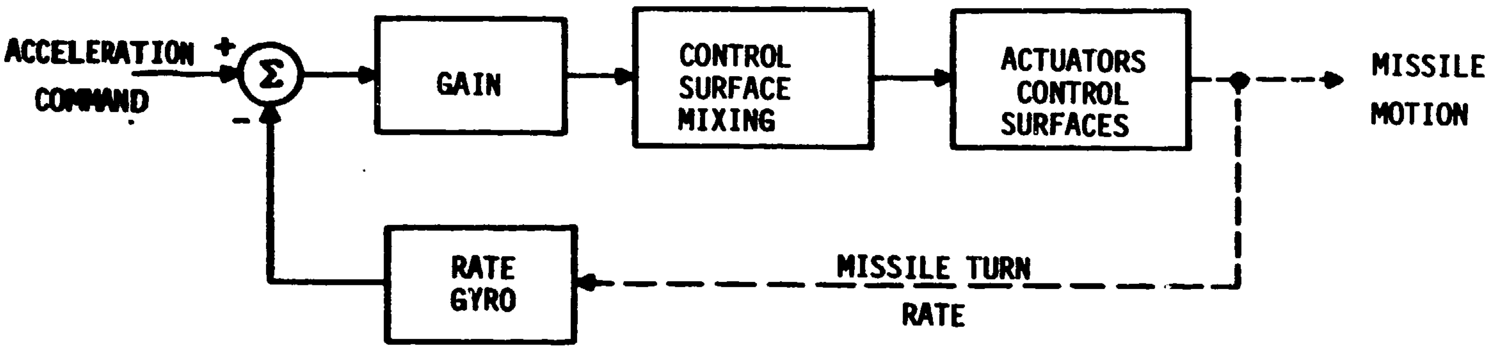
Fig. 16 REFERENCE AXES (Pitch, Yaw, Roll)

Missile autopilots of various types are employed to accomplish specific functions. Roll autopilots may provide roll position stabilization or roll rate stabilization. Lateral autopilots provide stabilization of pitch and yaw motion by increasing the airframe damping and compensating for aerodynamic instability with changes in the missile's center of gravity as rocket fuel is expended. Closed loop autopilots employ inertial sensors to supply a feedback signal generated by the missile's turning rate or lateral acceleration. The three common types of closed loop lateral autopilots are based upon feedback from one rate gyro, one accelerometer and one rate gyro, or two accelerometers, in each plane (pitch and yaw). Block diagrams of typical autopilots are shown in Figure 17.

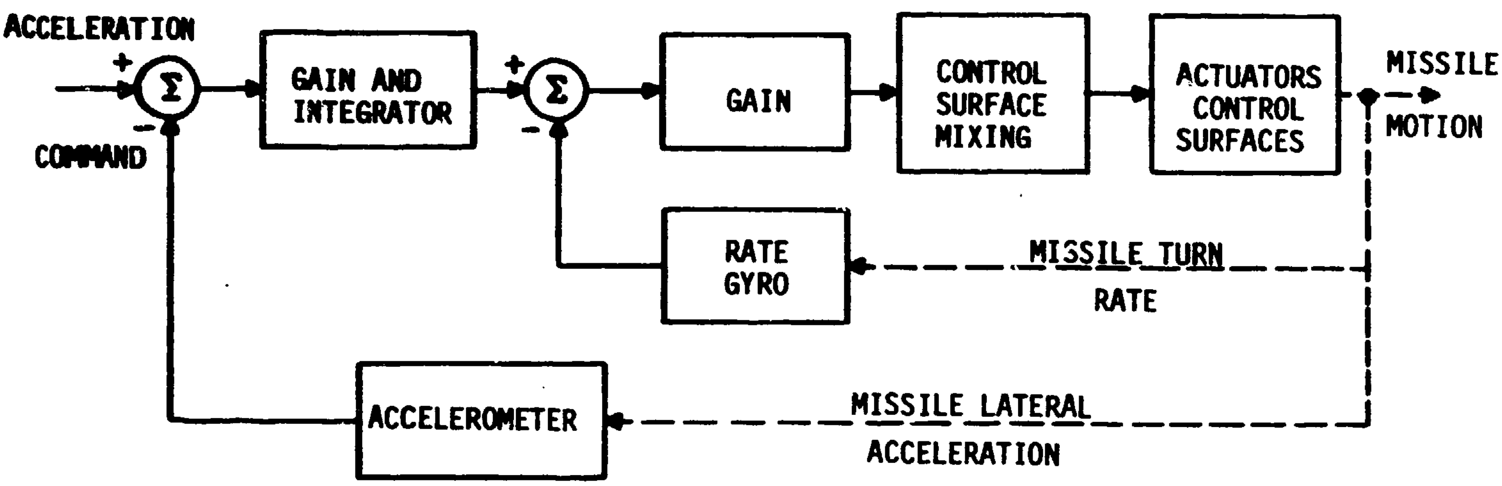
The guidance processor provides commands for corrective missile motion to the autopilot. These command signals are processed and sent to the control actuators to produce control surface deflections, which in turn result in missile airframe motion in the commanded direction. The autopilot acts as an interface with the actuators and may contain amplifiers, integrators, and mixing circuits for sending signals to the proper control surface actuators. In some missiles the control surfaces are offset from the pitch and yaw planes by 45°. To obtain pitch or yaw motion in such a case, both sets of control



a) Open Loop Autopilot



b) Closed Loop Autopilot Using Rate Gyro Feedback



c) Closed Loop Autopilot Using Rate Gyro and Accelerometer Feedback

Fig. 17 TYPICAL AUTOPILOT CONFIGURATIONS

surfaces must be deflected. Inertial sensors mounted on the airframe measure the achieved motion and provide an electrical signal which is subtracted from the motion command. Through such a feedback arrangement the control surfaces will be deflected until the missile achieves the commanded motion. When this occurs the inertial sensor output equals the commanded motion signal and there is no further input to the signal processor. To maintain the control surface deflection with no input, the processor must contain an integrator, as noted above and shown in Figure 17c.

The time of flight determines the type (accuracy) of gyros required by the missile autopilot. For short flight times, rundown gyros may be employed. These are activated just prior to launch by compressed gas or a cordite charge and coast (run down) during missile flight. Otherwise a sustainer-type gyro driven by an electric motor is required, which usually has higher accuracy and is more costly.

As mentioned already, the balancing of data input from the external target sensor (seeker) and the internal inertial sensors produces commands that are sent to the control actuators. These commands cause the PGM to maneuver.

3.7.5 Maneuver

In order to intercept the target, a missile must travel in the proper direction. At first throught this may appear to be a fairly simple procedure; however, upon further examination a multitude of factors influencing the ability to intercept a target can be recognized. The direction in which a missile travels is dictated by an algorithm built into the guidance processor known as the guidance law. Many different guidance laws have been developed over the years and with the advent of highly maneuverable airborne targets, research on improved guidance laws is continuing.

Perhaps the first guidance law that was implemented is known as pursuit guidance, resulting in a pursuit course, the "hound and hare" course. There are two kinds of pursuit courses: pure pursuit, where the missile velocity vector is always directed at the instantaneous target position, and deviated pursuit, where the angle between the missile velocity vector and the line-of-sight from the missile to the target is fixed. In the first case, the missile is always flying directly toward the target. In the second case, the missile flies with a fixed lead angle, anticipating the future target position.

Figure 18 illustrates target intercept based upon a pursuit course. Both pure and deviated pursuit trajectories are shown for the case of constant missile and target velocity, with the missile's velocity being twice that of the target. For the deviated pursuit course, a lead angle of 5° was used. For this particulate encounter the deviated pursuit course results in a slightly shorter missile flight and earlier intercept.

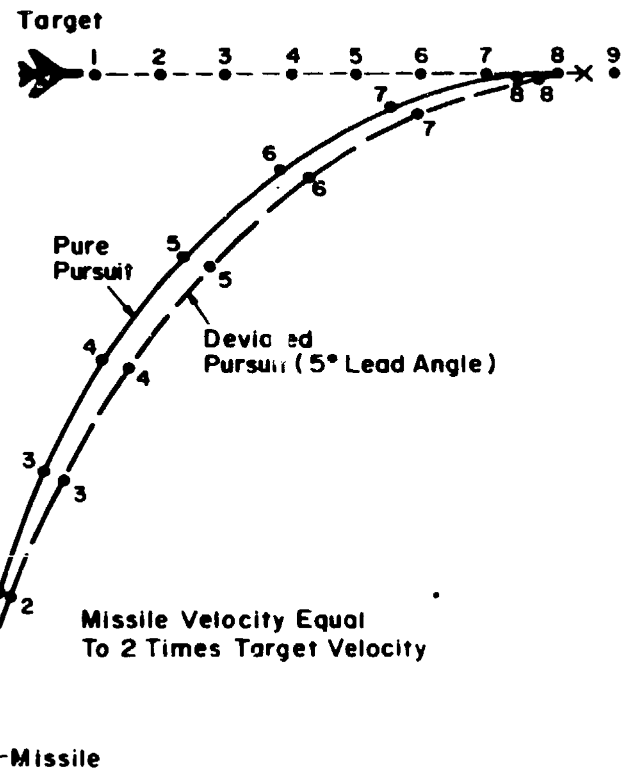


Fig. 18 PURSUIT GUIDANCE

Both of these guidance laws result in very high missile turning rates and lateral accelerat near intercept if the ratio of missile velocity to target velocity is two greater, for moving targets. The system is also very sensitive to angle errors in the boresighting of the directivity characteristics of the seeker's antenna/mirror system.

A more efficient and less demanding course can be followed by predicting the target path and directing the missile toward the predicted intercept point. This works well if the prediction is correct. Tnis can be

accomplished by controlling the missile's trajectory so as to keep the direction (line-of-sight) to the target constant, i.e. known as a constant bearing course. Figure 19 illustrates a constant bearing course for the same initial missile/target conditions shown in Figure 17. This is the optimum course that can be followed for the conditions stated: constant missile and target velocity, and non-maneuvering target. As shown, the line-of-sight between the missile and the target maintains a constant direction in space, i.e. the line-of-sight from missile to target always remains parallel to itself.

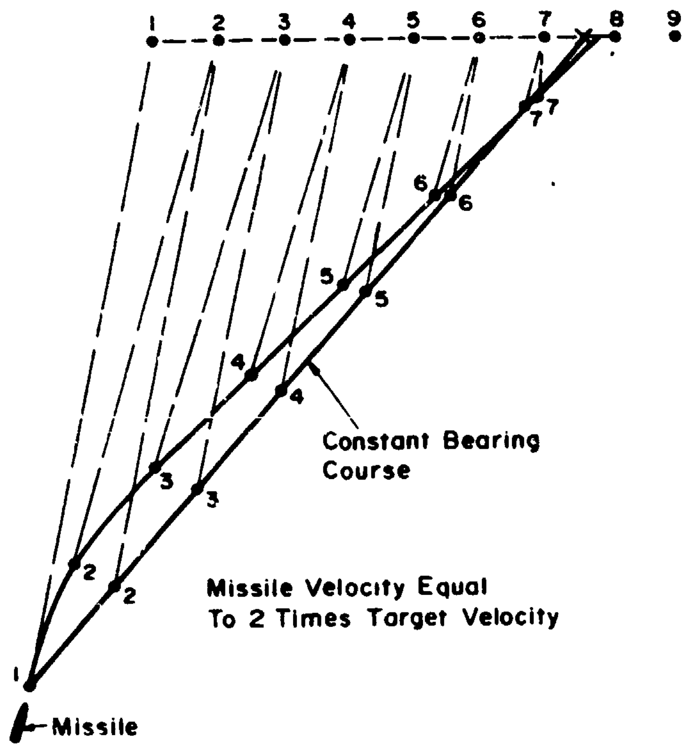


Fig. 19 PROPORTIONAL NAVIGATION

The fact that a constant bearing course results in a collision course led to the development of the proportional navigation guidance law. In proportional navigation, the rate of change in missile heading is directly proportional to the rate of rotation of the line-of-sight from the missile to the target. The purpose of such a course is to counter the tendency for the line-of-sight to rotate and hence to approximate a constant bearing course.

The trajectory of a missile operating with a proportional navigation guidance law is also plotted in Figure 19. A missile turning rate of three times that of the line-of-sight rotation rate was used to plot the trajectory. This factor is known as the navigation constant and is usually set at between two and four. The missile was launched in the direction of the target, as in the previous figures. The rotation of the line-of-sight is measured by the seeker which causes commands to be generated to turn the missile in the proper direction. With proportional navigation, the proper direction of flight is established shortly after launch, and missile then files on a constant bearing (collision) course to intercept the target. Most operational guided missiles employ proportional navigation.

However, the examples given do not represent real life situations. Constant velocity, straight line target flight paths present an ideal situation not likely to be encountered in combat. Viet Nam demonstrated that aircraft maneuvers could cause enemy surface-to-air missiles to miss. Missiles do not fly at a constant velocity either, but usually have a boost and coast or boost and sustainer type velocity profile. Their turning rate is also limited due to structural or aerodynamic stability constraints. Therefore, although the guidance law may call for high turning rates, the missile may not be capable of responding and will not be able to follow the intercept trajectory. In this regard, an advantage of proportional navigation over pursuit guidance is that fact that course corrections are made early in the missile flight. If the called for acceleration exceeds the missile's capability, there may be enough time left to achieve the proper flight path with the missile turning as rapidly as it can. In pursuit guidance, the maximum turning rates occur at the end of the flight where there is little time left.

With the development of highly maneuverable targets, pursuit guidance has become outmoded and proportional navigation has become somewhat of a marginal guidance law. New guidance laws are being developed that utilize more information about the missile/target encounter such as range, closing velocity, time to intercept, missile acceleration, and target maneuvers. Various digital signal processing algorithms based upon recent advances in modern control theory are becoming feasible with the advent of large scale

integrated circuits, which will permit the optimization of the missile's trajectory and expansion of missile launch envelopes.

Missile maneuvers are accomplished by causing forces to be generated on the missile to move it in the direction desired, i.e., to intercept the target. The forward motion is produced by the motor, which may be a rocket or jet engine, an explosive charge in the case of a projectile, or by the forward motion of the launch platform as in the case of a guided bomb. Lateral maneuvers (turns) are produced by aerodynamic control surfaces, jet reaction devices, or thrust vector controls.

Aerodynamic controls may be configured in a cartesian system, i.e., up, down, right, left, where a cruciform design is employed using two sets of controls to produce motion in any direction. Here, four control surfaces are spaced equally around the periphery of the missile body. A variation on this configuration employs a single set of control surfaces to produce single plane control. By forcing the missile to continually roll, activation of the single set of control surfaces at the proper time can produce motion in any desired direction. Although not as responsive as two sets of control surfaces, it is less expensive. This technique has become known as the rolling airframe missile and is employed by the STINGER missile.

Another control configuration employs what is known as the bank to turn system, where the missile is maneuvered like an aircraft. A monoplane design can be used which may have some aerodynamic advantages for certain missions.

Some guidance systems require the missile to be roll stabilized in order to sense direction properly, fix an image orientation, operate with a fixed signal polarization, minimize control surface activity, or maintain a gravity bias. In such cases the rolling airframe or bank to turn design cannot be employed.

Four common types of aerodynamic controls employed with missile systems are shown in Figure 20, together with fixed wings/fins for lift and stabilization. These control surfaces are deflected by actuators to generate aerodynamic forces which then act on the missile to produce a turning moment or lateral force, depending upon their location.

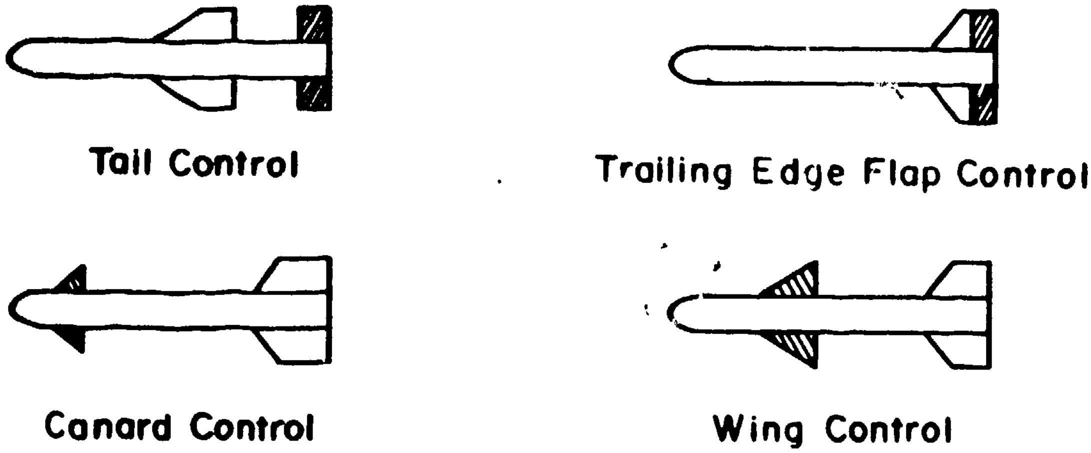


Fig.20 AERODYNAMIC SURFACE CONTROLS

Some important characteristics of these various control surfaces are discussed below. The details of the aerodynamics are very complex and difficult to analyze.

- Tail Control: The control surface is located behind the center of gravity of the missile; therefore, the deflection produces a force opposite to the desired direction of motion. The maneuver is accomplished by generating a turning moment which changes the angle of attack to produce a lift force in the desired direction. Being at the rear of the missile, the control surfaces are subject to the downwash/upwash fields from the body/wings forward of the control surfaces. These fields change rapidly with changes in angle of attack, making their prediction very difficult.
- Trailing Edge Flap Control: This type of control is generally associated with aircraft; however, it is employed in some missile systems. If the flap is hinged at the leading edge, the hinge moment is large, requiring a large actuator. Some compensating system, such as a mass balance or aerodynamic balance, is usually employed to generate a compensating moment to reduce the actuator requirements.
- Canard Control: Here, the control surface is located in front of the center of gravity of the missile so that the deflection produces a force in the same direction as the desired motion. This may result in a more rapid response than tail controls. Although there is no downwash/upwash effect on the control surfaces, they produce such effects on the tail surfaces which affect their lift. Because of these effects, canard control

is usually unsuitable for roll controlled missiles. Being near the guidance package, there is no need for connections running the length of the missile's airframe for control of the actuators, leading to a more compact guidance package.

- Wing Control: The control surfaces are located near the missile's center of gravity. Surface deflection produces lateral forces in the desired direction resulting in a fast response. Since little or no turning moment is generated, the range of the angle of body incidence is limited. This results in the following advantages:

  - operation of the guidance system may be improved through reduced radome error.

  - performance of air breathing propulsion systems may be improved through constant angle of attack.

  With wing control, the downwash effect on the tail is not as great as with canards, allowing roll control to be implemented.

The size and power requirements of a control actuator depend upon the hinge moment and moment of inertia of the control surface. The torque required to deflect the control surfaces partially determines the size of the control surface. The hinge moment depends upon the center of pressure of the surface. This varies with the angle of incidence, the control deflection, roll angle, and Mach number (velocity). By selecting the hinge line, the aerodynamic forces to be overcome can be partially balanced, however, this is a compromise based upon expected flight conditions. It is desirable to minimize both the hinge moment and moment of inertia in order to reduce the size and weight of the actuators and their power source. Electrical, hydraulic and pneumatic actuators have been used on various guided weapons. Where high torque and fast response is needed, the hydraulic type is usually employed. Pneumatic actuators obtain their power from either compressed gas, (stored cold gas actuator) or a burning fuel gas generator (hot gas actuator) resulting in long shelf life. These actuators fall between the hydraulic and electric actuators in terms of torque and response time and are generally employed on small missiles having relatively short flight time. Electrical actuators are becoming more common with the advent of new magnetic materials that permit high torque, lightweight electric motors to be built. They are usually used on missiles having long flight times, i.e., cruise missiles.

Two types of control systems are employed in missiles. In one, the actuators produce a deflection of the control surface that is proportional to

the magnitude of the maneuver called for by the guidance system, similar to that used in airplanes. This is the more efficient type in terms of aerodynamic drag. The other type, known as a "bang-bang" system, causes the control surfaces to deflect to either extreme position, depending upon the direction of the called for maneuver. A variation of this technique continuously alternates the control surfaces between their extreme positions, with the duration controlled to favor the position producing motion in the commanded direction.

An area of concern in missile control is that of cross-coupling. This results from forces produced in directions different from the primary forces expected from a deflection of a control surface. These secondary forces that affect missile motion vary with the angle of incidence, roll position, and flow patterns generated by the control surfaces as they deflect. In general, each surface is controlled independently (not in pairs) to produce pitch, yaw, and roll, leading to different deflections for each control surface. This complex situation results in cross-coupling due to the secondary effects produced.

Two other types of missile control will be mentioned for completeness. Jet reaction control is based upon a gas jet exhausted from the surface of the missile. This produces a lateral force to control the missile's trajectory. It is capable of producing a force in the absence of an external air stream, so it is effective at very low velocities and at very high altitudes. It has been employed on an antitank missile (DRAGON), where small charges, located around the missile body, are fired to produce the desired lateral movement. This is illustrated in Figure 21. Thrust vector control operates by deflecting or controlling the jet stream from the missile propulsion unit. This applies a turning moment directly to the body for trajectory control. The technique is applicable at low speeds and high altitudes where aerodynamic controls are inefficient. It may also be employed where rapid high "g" maneuvers are required, such as in a short range air-to-air missile. It requires the motor to burn while it is being used and is commonly used when launching space vehicles. Examples of thrust vector control using a movable nozzle and deflection vanes in the exhaust stream are given in Figure 22. The latter was used in the German V-2 and is used in the PERSHING missile.

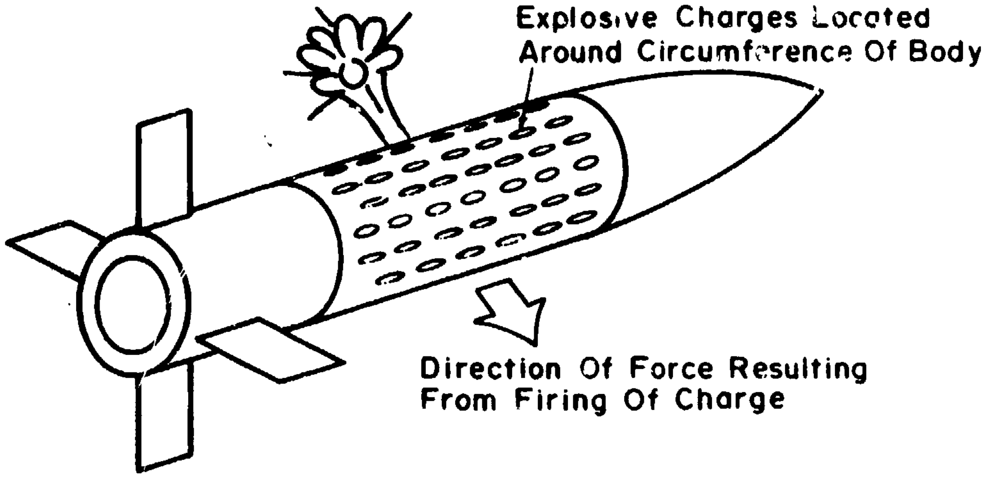


Fig. 21 EXAMPLE OF JET REACTION CONTROL

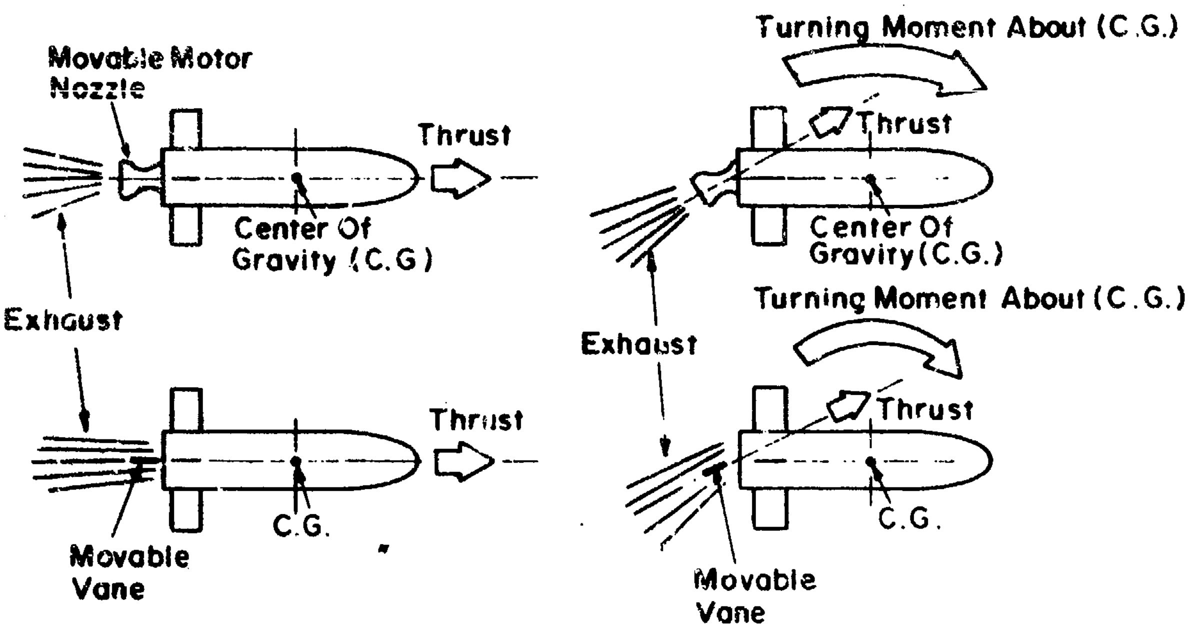


Fig. 22 EXAMPLES OF THRUST VECTOR CONTROL

3.7.6 Fuze

Most PGMs have a separate fuze to detonate the warhead at the proper time and to provide safety during handling, storage, testing, and launch. These functions are provided by two devices known as the target detecting device (TDD) and the safe and arming device (S&A). The target detecting device is designed to match the mission of the PGM, and may sense physical contact with the target (a contact fuze) or sense the closest approach to the target (a proximity fuze). Contact fuzes are usually mechanical devices, but may employ electrical switches to ignite the warhead. They are generally used in bombs, projectiles, and antitank weapons. Proximity fuzes sense the target using some type of energy, i.e., visible, infrared, radar, magnetic, etc., and may operate in an active, semiactive, or passive mode. These terms have the same meaning as when used to define guidance modes in Section 3.1. Proximity fuzes are generally used against air targets because of the speed of the final engagement and the difficulty in actually hitting a highly maneuverable vehicle. Warhead detonation timing is critical in these situations and can be controlled very accurately by sensing closing velocity, range, or angle of intercept.

The safe and arming device controls an interrupter that is positioned between the detonator and main warhead charge. The main warhead charge is fairly insensitive to accidental detonation and requires a large shock, as provided by the detonator, for initiation. When in the safe position, the interrupter prevents propagation of the firing signal to the warhead, so that it cannot be detonated.

The fuze is armed by a combination of acceleration or setback, lasting for a known period of time, and a time delay. This prevents arming due to shock that might be experienced if the missile is dropped. It also provides enough time for the missile to achieve a sufficient distance from the launcher to allow warhead detonation without endangering the launcher.

3.7.7 Warhead

The primary objective of any PGM is to neutralize or destroy a target. All of the other components of the PGM are intended to maximize the effectiveness of the warhead by guiding it to the optimum position and initiating detonation at the proper time. Warheads for precision guided munitions may be

grouped into a number of major categories as follows: blast, fragment, rod, and shaped-charge. Variations and combinations are also employed, such as the self forging fragment and heavy metal kinetic energy warheads being developed for use against armor.

A warhead that propagates its energy and material uniformly in all directions as an expanding sphere is known as an isotropic warhead. Such a warhead produces equal damage effect at a given distance for all directions. An isotropic blast warhead is designed to damage targets by subjecting the target surface to extreme pressure. An expanding high pressure shock wave is generated in the surrounding atmosphere by the exploding warhead. This shock wave propagates at approximately the speed of sound, Mach 1. Since the pressure volume expands spherically, the pressure falls off with volume, or inversely as the cube of the distance. If the overpressure generated by the warhead is proportional to weight, for a given type of explosive, the maximum range of damage is proportional to the cube root of the warhead's weight. Figure 23a illustrates a blast type warhead.

Fragmentation warheads consist of an explosive change surrounded by a wall of pre-formed metal fragments or a scored solid metal casing. Upon detonation of the explosive, the metal fragments are propelled outward at high velocities. Target damage is produced by these fragments impacting vital structural or control elements of the target, causing physical failure. If the fragments form an expanding spherical shell with uniform distribution of fragment weight per unit shell area, the warhead is an isotropic fragment warhead, producing equal damage at any given range in all directions. Since the area of the expanding spherical shell increases as the square of the radius of the sphere, the fragment density falls off inversely with the square of the radius. If all other parameters are constant except weight, the maximum range of damage for such a warhead is approximately proportional to the square root of the weight. Figure 23b illustrates an isotropic fragment warhead.

Now consider a fragment warhead where the fragment pattern is confined to a small circular sector or cone about the longitudinal axis of the missile. This results in an expanding ring of fragments, where the fragment density falls off inversely with the radius of the ring. This results in a warhead that will show a maximum damage range that is proportional to warhead weight,

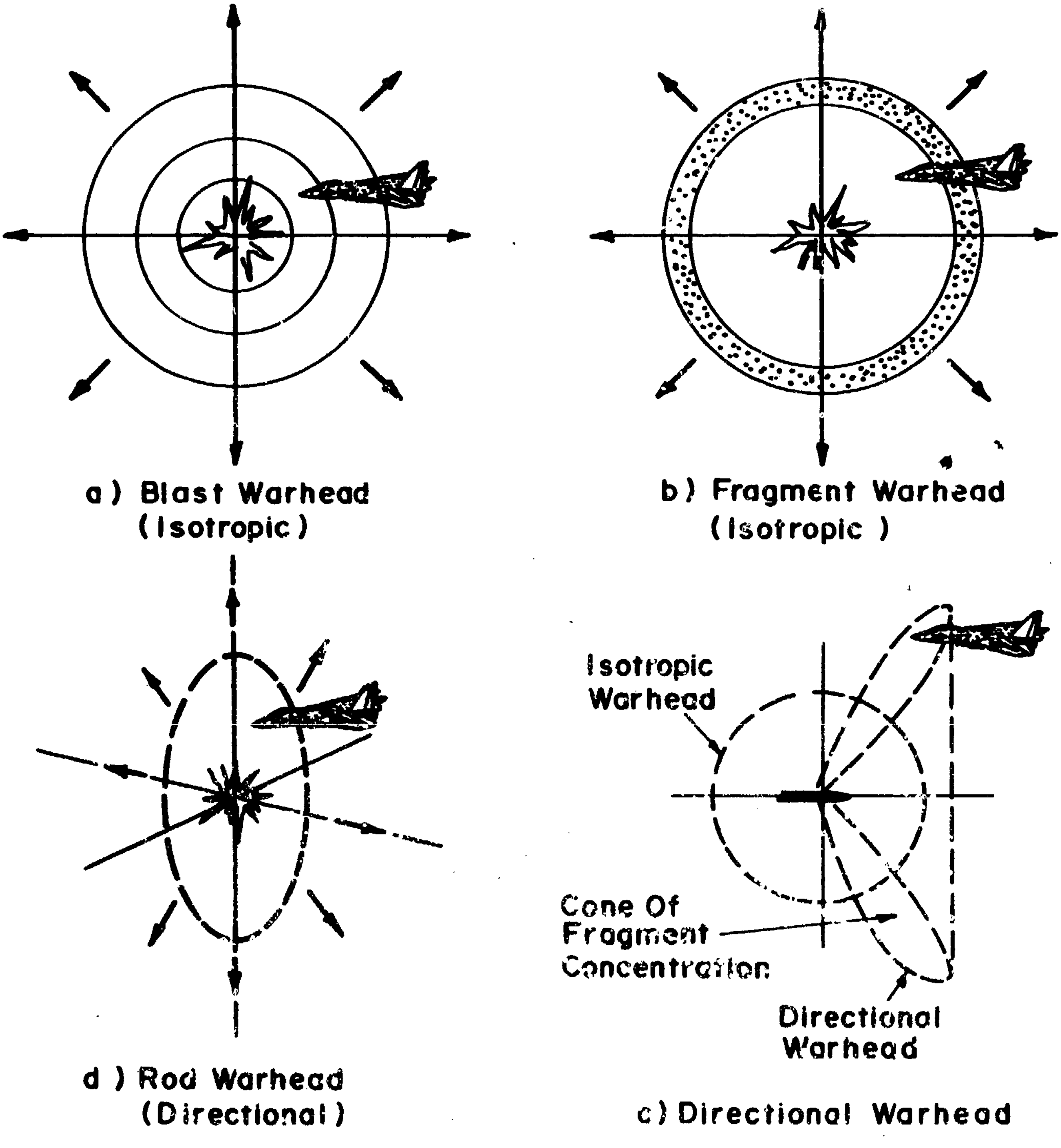


Fig. 23 TYPES OF WARHEADS

assuming all other parameters are constant. Obviously such a warhead is not isotropic, and is known as a directional or non-isotropic type warhead. Figure 23c illustrates one type of directional fragmentation warhead.

Another type of directional warhead employs rods that are connected at each end so as to form an expanding metal ring. Such a warhead is constructed by placing the explosive charge within a metal cylinder made up of performed rods or a scored metal casing. Upon detonation, the sections are propelled outward to form a continuous ring. This ring is intended to damage the target (usually an aircraft) by cutting major structural components. Figure 23d illustrates the rod warhead.

Directional warheads require proximity fuzes that are capable of detecting the target and detonating the warhead at the proper time to inflict maximum damage. As the directionality of the warhead is increased, performance requirements of the fuze are also increased. This area is one of continuing interest, especially as missiles become smaller. As discussed, the maximum damage range is proportional, in some way, to the warhead weight, and by increasing the directionality the damage range can be maximized.

Shaped-charge warheads were developed mainly for use against armor. They provide a narrow beam or jet of metal due to the rapid collapse of a cone-shaped metal liner located at the forward end of an explosive charge. Upon detonation, the metal liner produces a jet of ultra-high velocity metal that is capable of penetrating into large thickness of material. A shaped-charged warhead must impact the target to be effective. Self-forging fragment, or explosively formed penetration, warheads are being developed for PGMs that are similar to the shaped-charge warhead, but they form the high velocity metal fragments. These metal fragments then penetrate the armor in a manner similar to that of a shaped-charge.

Heavy metal kinetic energy warheads are being investigated for use in hypervelocity missiles, where the kinetic energy produced by the high velocity of a heavy metal slug (tungsten or depleted uranium) is employed to penetrate armored vehicles or hard targets.

3.7.8 Interfaces

A PGM is a highly integrated combination of components. As already indicated, each of these components is tied together, usually through the

central processor. This means that each of the components, sensor, seeker, control actuators, inertial sensors, fuze, and warhead, must be able to provide a compatible signal to the processor. Some of the components have an analog output while others may be digital. Electronic devices serve as interfaces to provide a compatible hook-up. Recent advances in microprocessors are leading to the development of new techniques known as distributed processors which allow some sharing of the computational load.

There are other components, such as: prelaunch signals, electrical power, command links, auxiliary beacons, and maintenance test connections that need to be integrated within the system. The central processor may also couple to these components through compatible interfaces.

Thus, by compiling all of the various components together through compatible interfaces, a smart weapon system can be developed to perform seemingly impossible missions.

3.8 Conclusion

How do smart weapons work? They are a complex combination of components consisting of a sensor mounted in a seeker which tells where a target is, coupled with an autopilot to control the missile, interfaced together with a guidance processor which interprets the sensor data for use by the control system. A tremendous amount of technology has gone into the development of smart weapons, much of it borrowed from other scientific fields. From this discussion it should be obvious that the smart weapons are based upon principles taken from radar, optics, infrared technology, electronics, information theory, aerodynamics, control systems, computers, rocketry, dynamics, explosives, and mathematics. Advances in semiconductor technology have given impetus to the recent surge in smart weapon development by providing the computational power necessary to solve highly sophisticated relationships and interact with sensor outputs in real time, creating the "smarts" of a smart weapon system.

4. WHAT GOES INTO THE DESIGN OF A SMART WEAPON SYSTEM?

4.1 Introduction

A seeker cannot be developed independently of the missile or the missile developed independently of a weapon system. A smart weapon or PGM is just one part of a total system. That total system could include complete integration within a combined arms team. The force-multiplier effects resulting from PGMs may not be possible without the synergistic influence of all the contributors to the total system. For example, the maximum effectiveness for some laser guided weapons such as HELLFIRE and COPPERHEAD depend upon integration of signal, armor, infantry, and field artillery components. The design of any PGM must anticipate and consider all of the potential interactions involved.

The ultimate objective of building any PGM is to provide the user with some way to defeat or neutralize the enemy. Perceptions of threats posed by the enemy, when compared to the ability to meet that threat, may dictate the need for a new weapon system, an improvement in a fielded system, or no change at all. The case for PGMs requires some new thinking in terms of this classic response to a threat. In the past, the basic concept of a threat was summarized in the statistical probability of an exchange ratio of casualties based upon throwing masses of munitions against each other. These munitions had a low kill probability so that 10 to 1000 rounds were necessary for each kill. If troops could dig in or find a place to hide, the effectiveness would be even lower. On the other extreme, the frightening thing about nuclear weapons is that they appear to have a kill probability of one to everyone in the world, no matter where they are aimed and it appears to be impossible to hide from them. PGMs now pose an in-between threat. If a target can be seen, it can be hit; if it can be hit, it can be killed. This sort of threat is new to warfare. Because of the lack of experience against such a threat, effective tactics have not been developed. Without tactics it is not possible to properly respond to the threat.

The point of this discussion is that the design of any PGM depends upon a total analysis of the battlefield and the opposing combined arms, without losing sight of the fact that the battlefield of the future will be changed

because of the very presence of PGMs. Doctrine and tactics have not caught up with this threat, especially for the case of PGM versus PGM.

4.2 Missions

From a formal perspective, great emphasis is now placed upon studying and analyzing the missions that weapons must perform. Mission analyses must be performed as a preliminary step towards deciding on how to combat a threat. In this process, mission areas are designated based upon functions of the troops countering the threat. Because of differences in roles and missions among the Services, a standard set of mission areas is yet to be adopted. In the case of PGMs, there is general agreement on how to describe the missions (as opposed to air defense, fire support, interdiction, and close combat). Missions are defined by specifying first the location of where a missile is launched from and then stating where it is going to: air-to-air, air-to-surface, surface-to-surface, and surface-to-air. The variation from this rule is applied to undersurface PGMs deployed by the Navy. Since this nomenclature is so widely used, an attempt will be made to develop a standard schematic approach that is keyed to the nomenclature. The following five diagrams in Figures 24-28 briefly describe each of the missions listed in Figure 1. In every case, the launcher is on the left, the missile is in the middle, and the target is on the right. Each diagram is different and is unique to the mission. Wherever the same arrangement of coordinate points is used throughout this report, the mission will be the same. For example, all the diagrams in the surface-to-surface section of the handbook will be similar to that shown in Figure 24. Other data may be added, but the relative positions of the points will be the same. The lines drawn show possible data links or sensor transmission paths employed by the PGM.

4.3 Applications

Throughout this tutorial the term "missile" has been used as a generic representation of all PGMs. Although most PGMs are missiles, PGM does not stand for precision guided missile, but for precision guided munitions. Any explosive or kinetic energy payload which receives instructions in flight to change its direction in order to have a probability of hitting the target more than 50 percent of the time is a PGM. Tactical missile PGMs can perform all of the different missions outlined and be rocket, ramjet, or turbojet powered.

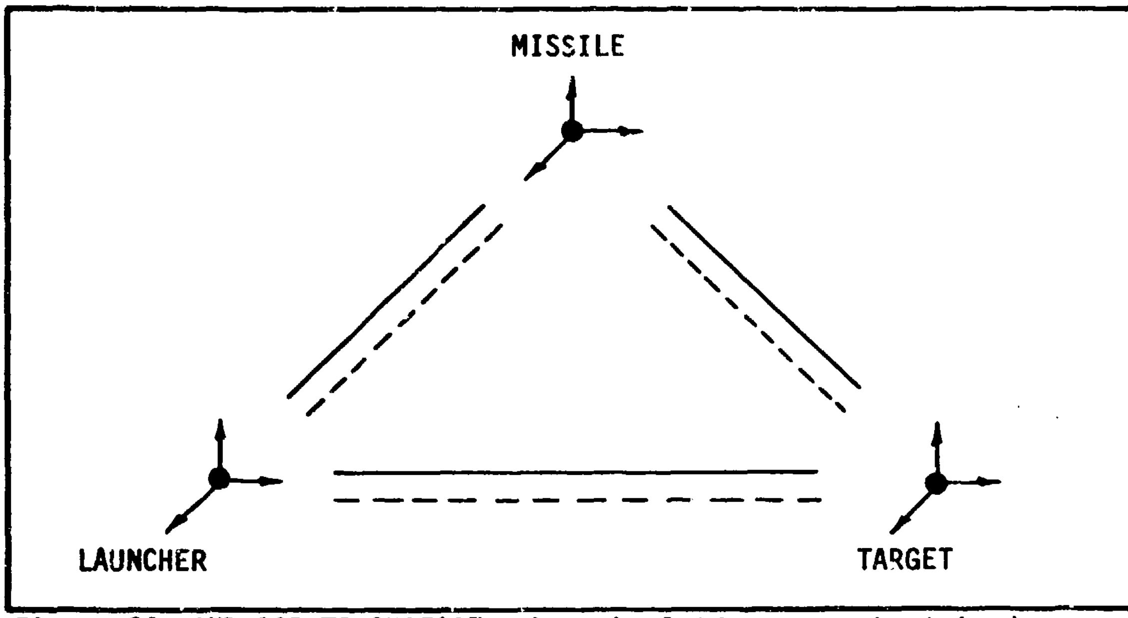


Figure 24 SURFACE-TO-SURFACE: Launch platforms may be tripods, ground vehicles, cannon tubes, or ships. Targets may be at ranges of one to greater than 1000 kilometers and consist of tanks, ships, men, materiel, and fortifications. Primary interest is by the Army, Navy, and Marines.

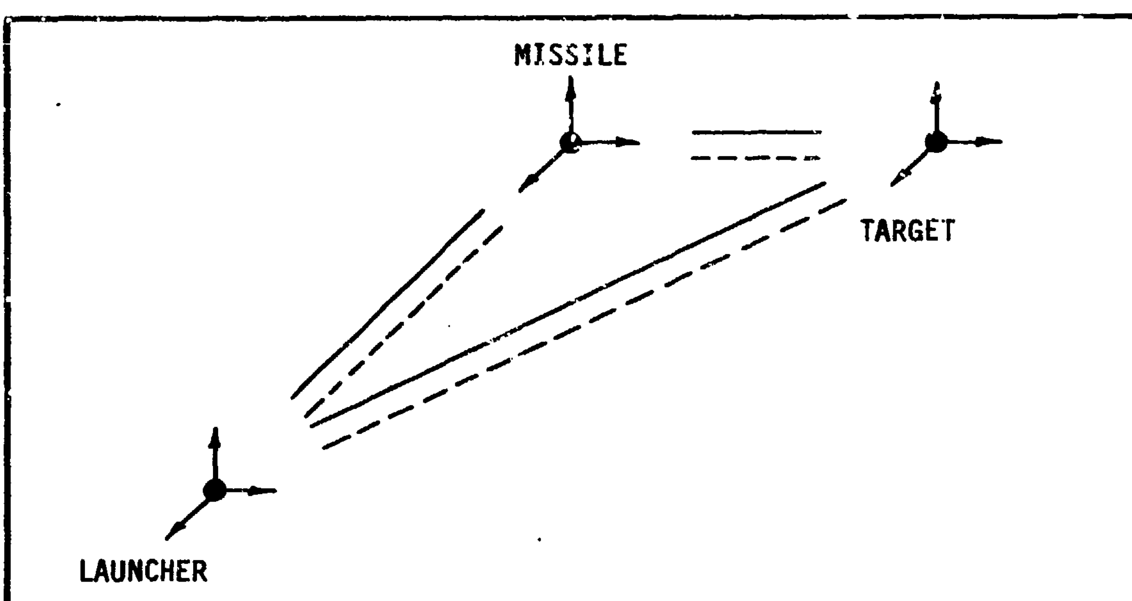


Figure 25 SURFACE-TO-AIR: Launch platforms may be shoulder-mounted, tripods, ground vehicles or ships. Targets are airborne helicopters, fighters, missiles, bombers, and supporting aircraft at ranges of one to greater than 500 kilometers. Primary interest is by the Army, Navy, and Marines.

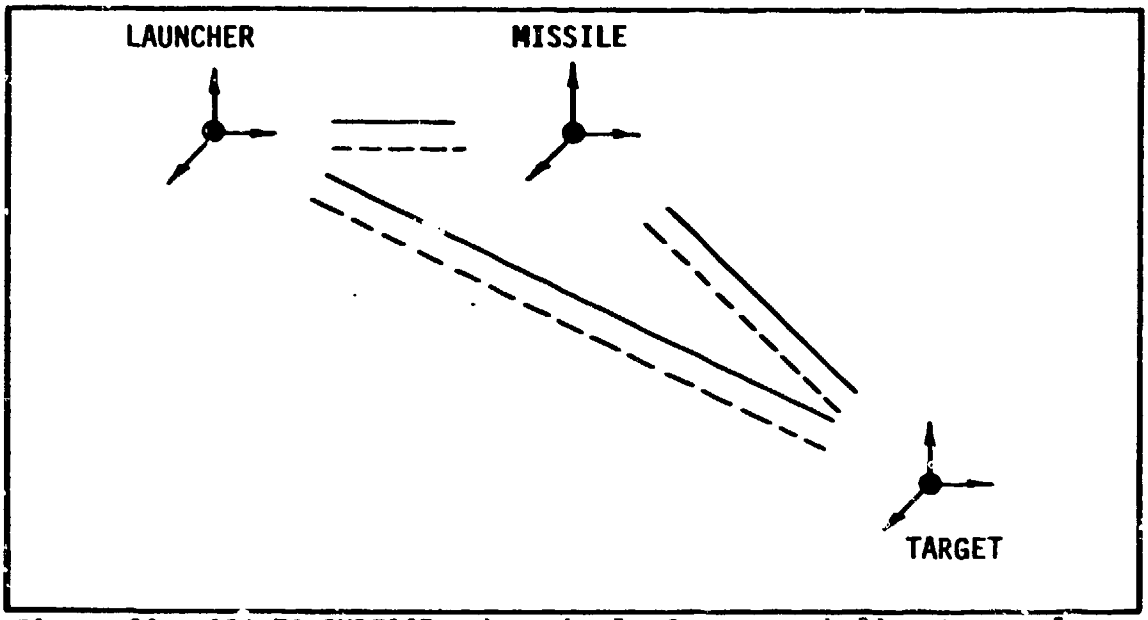


Figure 26 AIR-TO-SURFACE: Launch platforms are helicopters, close-air support fixed wing, fighter aircraft and bombers. Targets may be any enemy high-value assets' including men, tanks, vehicles, materiel, air fields, SAM sites, bridges and ships. All three Services and the Marines have an interest.

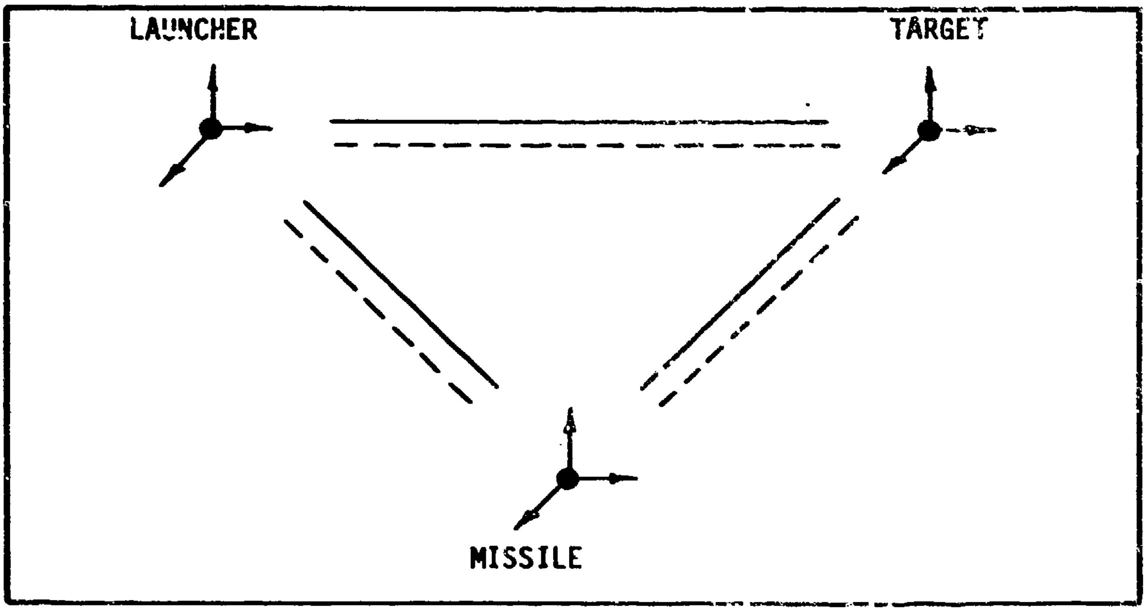


Figure 27 AIR-TO-AIR: Launch platforms are primarily fighter aircraft and bombers. Self-defense systems for helicopters are under consideration. Generally, targets are of like kind at ranges from three to 150 kilometers. Navy, Marines and Air Force have major interest.

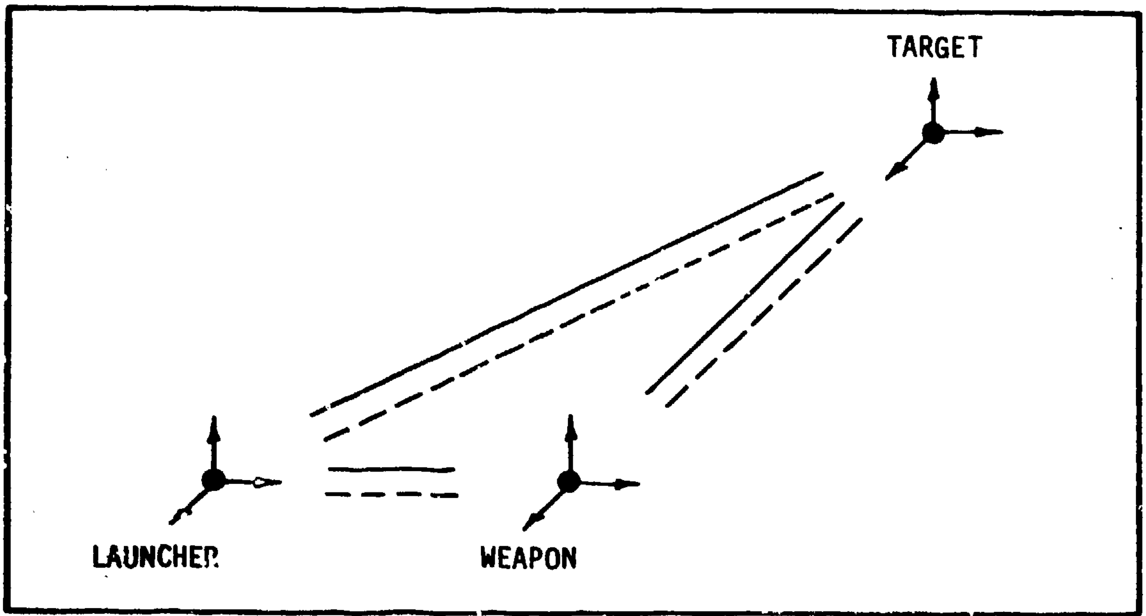


Figure 28 UNDERSURFACE: Launch platforms are submarines, ships and sometimes aircraft. Targets are enemy submarines, ships, and aircraft at one to 100 kilometers. Weapons may be mines, torpedoes or missiles. The Navy and Air Force have interests in this area.

4.3.1 Projectiles

Another application for PGMs is projectiles. Projectiles are lau... ed from a gun tube on a ballistic path. Launching may involve very high setback forces of 15,000-20,000 times the force of gravity. Guidance and control components must, therefore, be hardened to these forces. Projectiles may have their ranges extended by the addition of rocket-assisted propulsion (RAP) or, in the future, with a ramjet. With the addition of control surfaces, the projectile gains many of the maneuverability characteristics of a missile. Guided projectiles allow artillery to hit point targets rather than be the area weapon they have been in the past and may provide higher accuracy in gun systems designed for use against point targets. Projectiles as PGMs have primarily been used for Army and Navy missions.

4.3.2 Bombs

The impetus for the new emphasis on PGMs was probably the success of guided bombs used in the Southeast Asia conflict. Smart bombs are much more ffective than dumb bombs. The addition of precision guidance allows the delivery of hundreds and even thousands of pounds of explosive in one device squarely on target. Because of this capability, warfare may never again see the 1000-plane bombing raids that were so devastating in World War II. The threat of the guided bomb forces dispersion and digging in. There is also the added ability of the guided bomb with glide characteristics to be deployed from a standoff range to decrease the vulnerability of the carrying platform. The Air Force has been the primary proponent of precision guided bombs; however, the Navy and Marines also employ these weapons.

4.3.3 Submunitions

The increased interest in the adaptation of PGM characteristics to submunitions is an excellent demonstration of the three technical developments that made PGMs possible in the first place. The first advance was in the development of high-resolution sensors that could be put in a small package. The second achievement was the development of microelectronic circuits. The third accomplishment was the development of highly efficient warheads. All of these developments come together in a terminally guided submunition (TGSM). Submunitions are individual warheads loaded into a common carrier or bus for dispensing over the target area. Two to 50 or more submunitions can be carried in a cluster. Each individual submunition has the capability to sense a target, direct itself in flight towards the target, and attack the target. One particular warhead approach being developed is the self-forging fragment or explosively-formed penetrator, which is like a cannon in the sky. The warhead is fired 10-100 meters from the target. The metallic mass of the warhead is explosively shaped into a single slug that travels at 2000-3000 meters per second to hit the target. Instead of being referred to as a TGSM, these weapons are known as sensor fuzed munitions. They employ an infrared or millimeter wave sensor aligned with the firing direction of the self-forging fragment (SFF). When a target is detected based upon the particular logic, the SFF is fired in the proper direction to impact the target. The Army and the Air Force are both interested in exploiting precision guided submunitions for use against enemy armor.

4.3.4 Mortars

With further miniaturization of sensors and accompanying components, there is a growing interest in developing smart mortars. Mortars are generally fired out of short tubes in a ballistic path at area targets. If they could be used against point targets, their effectiveness would be dramatically improved. Both the Army and Marines could benefit from such a capability.

4.3.5 Target Activated Munitions

Another type of PGM currently under development is known as target activated munitions. These weapons are employed against ground targets and have the ability to detect the presence of a target through acoustic or seismic sensors. They may be scattered in the vicinity of known targets and lay in wait for a target to approach, similar to mines (which are generally thought of as requiring target contact). Upon the approach of a target(s), the munition is activated and fired into the air, where it searches for and is guided toward the nearby target, generally an armored vehicle. By aiming for the top of the vehicle it attacks the most vulnerable area.

4.3.6 Undersurface

The Navy has a need for PGMs that stay underwater, enter the water and attack underwater or surface targets, and possibly exit the water to attack airborne or surface targets. Very unique demands on guidance and control are required for this environment. Here, acoustic and magnetic sensors are exploited even more so than in the other applications.

4.4 Operational Functions

Discussion so far has concentrated on the missile that flies to the target. A smart weapon system is much more involved than the missile. Figure 1 has a block which describes all of the operational functions that a smart weapon system must perform. First, there must be some means of surveillance of an area where there might be enemy targets. The surveillance system must have a built-in capability to detect, recognize, and acquire targets. Once acquired, there may be a need to track a target so as to continually update its position. These operations of surveillance, acquisition, and tracking may be conducted with a single unit or multiple combinations of radar, infrared, optical, or other devices. Normally, these

three operations are performed by equipment auxiliary to the missile. Initial surveillance may frequently be performed by an airborne platform or forward observer who is quite remote from the actual unit that fires the missile. In this case a communications link or some command authority over the fire unit is needed. The surveillance organization will transfer verbal or digital coordinate or zone information on the exact or approximate target location and direction of movement so that more precise acquisition and tracking may be performed.

Surveillance is usually performed by a system that has a large field of view and can search a large volume or surface area quickly. After detection of a possible target, acquisition and tracking can use progressively narrower fields of view. Usually in the process of acquiring and tracking a target there is an additional operational function of determining whether the target is an enemy or not. This process is known as identification, friend or foe (IFF). In the complex world of limited conflict and in the presence of non-combatants, IFF is extended to include identification, friend, foe, or neutral (IFFN). The process of IFFN is normally done by querying a system in a coded message and receiving an acceptable, previously agreed-upon coded response. Neutral intruders may not have the capability to respond. The enemy definitely should not. Moreover, the problem with modern electronics is that the query is a notice to a potential enemy target that he may soon be under attack. There is a very great demand for a non-cooperative IFFN capability, particularly passive, that does not give advance warning of a potential attack. The problem of IFFN has historically been a problem with aerial targets. With the advent of highly mobile surface combatants, the possible friendly use of captured enemy equipment, or vice versa, and foreign military sales of American and Allied equipment, the IFFN issue has become a significant problem both on the ground and in the air.

As a result of this requirement, a considerable amount of work is being done in the area of non-cooperative target recognition. Here, complex signal processing systems are being investigated to permit unique target signature characteristics to be extracted that may lead to the identification of particular types or classes of targets. However, this will not solve the problem of enemy use of captured or purchased friendly equipment and this issue will probably remain a problem.

The functions of surveillance, acquisition, tracking, and IFFN are all considered component functions of a fire control system. At some point there must be a handoff to the PGM. This handoff may be performed either before or after launch of the PGM. As defined earlier, if the handoff occurs before launch, the process is referred to as lock-on-before-launch (LOBL). If the fire control system is self-contained on the launcher, this handoff process requires an accurate boresight harmonization with the fire control system. If part of the fire control unit is remote from the launcher, then the position coordinates of the fire control unit must be related to those of the launcher. The handoff process can be completely automatic, with selected PGMs automatically cued to different targets. In some cases all of the operational functions of surveillance, acquisition, and tracking are performed by the missile seeker with supporting IFFN equipment, and the gunner in the loop is expected to function only as an interrupt or to pull the trigger. In this case, all of the operational functions can be left to the PGM after it is launched. The fire control system is used only to launch the missile into an area or basket. Once in the basket, a separate fire control system can take over command of the PGM, or the PGM can go through all of the operational functions as a LOAL weapon. If the PGM is to perform its mission, it must achieve lock-on and maintain it through the terminal engagement with the target.

In performing its operational functions, every PGM is characterized in terms of its operational envelope or for surface targets, its footprint. Usually, a PGM will have a dead-zone near the launcher where kinetic parameters will not permit maneuvers against certain targets. This dead-zone is also created by minimum safe distances for the weapon fuze to be armed in flight. At the outer boundary, the PGM no longer has enough kinetic energy to go after a maneuvering target. Propulsion can be maintained for only so long before the PGM falls out of the sky.

Finally, it is highly desirable to know what happened to the PGM after it was launched. Did it hit the target? Was the target killed? Some form of kill assessment is needed. The target may disappear from the radar screen. The target may be observed to go down, or the enemy never appears where he was headed. Kills are rated in different ways. A K-kill is complete. An M-kill, or mobility-kill, prevents the enemy from moving. Abort of a mission may be

as good as a kill. It is important in the era of PGMs to know which targets are killed so that valuable assets will not be wasted against dead targets.

4.5 Components

The primary components of the PGM itself were discussed in Section 3. It should be plain by now, especially after the discussion on operational functions, that a PGM weapon system is more than a missile or projectile. It is a combination of devices including fire control, communications, and launchers. The system is even much more than this. Support vehicles, maintenance equipment, spare parts, resupply and reload capability, special training devices, adaptation kits, modular add-on's, troop support needs, power supplies, connecting cables, and all sorts of items make up the total system. Last, but more important than anything else, employment of PGMs takes manpower. These personnel must be available in the right numbers and with the required training. The use of PGMs does provide a force-multiplier effect, but troops are needed to make this possible.

4.6 Target Sensing

All input information provided to a PGM before and after launch is obtained through various types of sensors. Generally these sensors are radar, infrared, or optical systems used to gather data about the target's location and/or velocity in order to launch or fire the PGM at the proper time and in the right direction to hit the target, and to provide guidance information during the flight to correct any errors in the intercept trajectory. Most sensors of interest operate by receiving electromagnetic energy in some part of the electromagnetic spectrum. A brief review of the spectrum is necessary to gain an understanding of why various sensors are employed for fire control and guidance.

4.6.1 Review of Electromagnetic Spectrum

The electromagnetic spectrum has been divided into various ranges or bands based upon the characteristics of the signals lying within the band. The terms radio waves, microwaves, infrared, light, ultraviolet, X-rays are all well known, and represent loosely defined portions of the spectrum. Various nomenclatures have been attached to portions of the spectrum which leads to confusion, even to those working in the field. A frequency designation system divided into decades is the oldest standard system for

identifying the frequency bands. In some of the highly used radar bands, this was too coarse, and smaller frequency ranges were identified by code letters during the WWII (probably for security reasons when radar was being developed). In the late 1970s, the Joint Chiefs of Staff introduced another set of letter codes identifying frequency bands associated with electronic warfare. The radar developers never accepted these and came up with a set of letter coded bands similar to the original WWII version, but using rounded numbers. Figure 29 presents a summary of the different bands and defines two new bands for the first time.

A number of portions of the spectrum are utilized in guidance and control for data and command links as well as for target sensing. Sensors employed in PGMs generally operate in the SHF, EHF, and EOF bands; however a brief description of all of the basic decade bands and their significance to guidance and control will be given in the following paragraphs.

4.6.1.1 Ultra Low Frequency (ULF)

The ULF band runs from 3 to 30 cycles per second or Hertz (Hz), with wavelengths of 10^4 to 10^5 kilometers. ULF is characterized by extremely low bandwidth information capacity and deep penetration into seawater and earth. Subterranean wave-guide propagation modes are predicted. With communications considered the only practical application, this band is always a consideration for minimum essential emergency communications networks, especially as a bell-ringing warning to submarines. The extremely long wavelengths, which are generally greater than 10^7 meters, make efficient radiation very difficult. The complex interaction of radiation with propagation media is not well understood. Propagation from sources placed in the magnetosphere, ionosphere, or lithosphere continue to be studied with source generation using perturbations on natural processes being major topics for investigation. Answers are really needed to determine practical possibilities, but results are slow in coming. There is very little application of this portion of the spectrum to guidance and control, or to other uses.

4.6.1.2 Extremely Low Frequency (ELF)

The ELF band runs from 30 Hz to 3 KHz or two decades with wavelengths of 100 to 10,000 kilometers. Very low information bandwidth capacity is also exhibited by systems using this band. It has good penetration into seawater

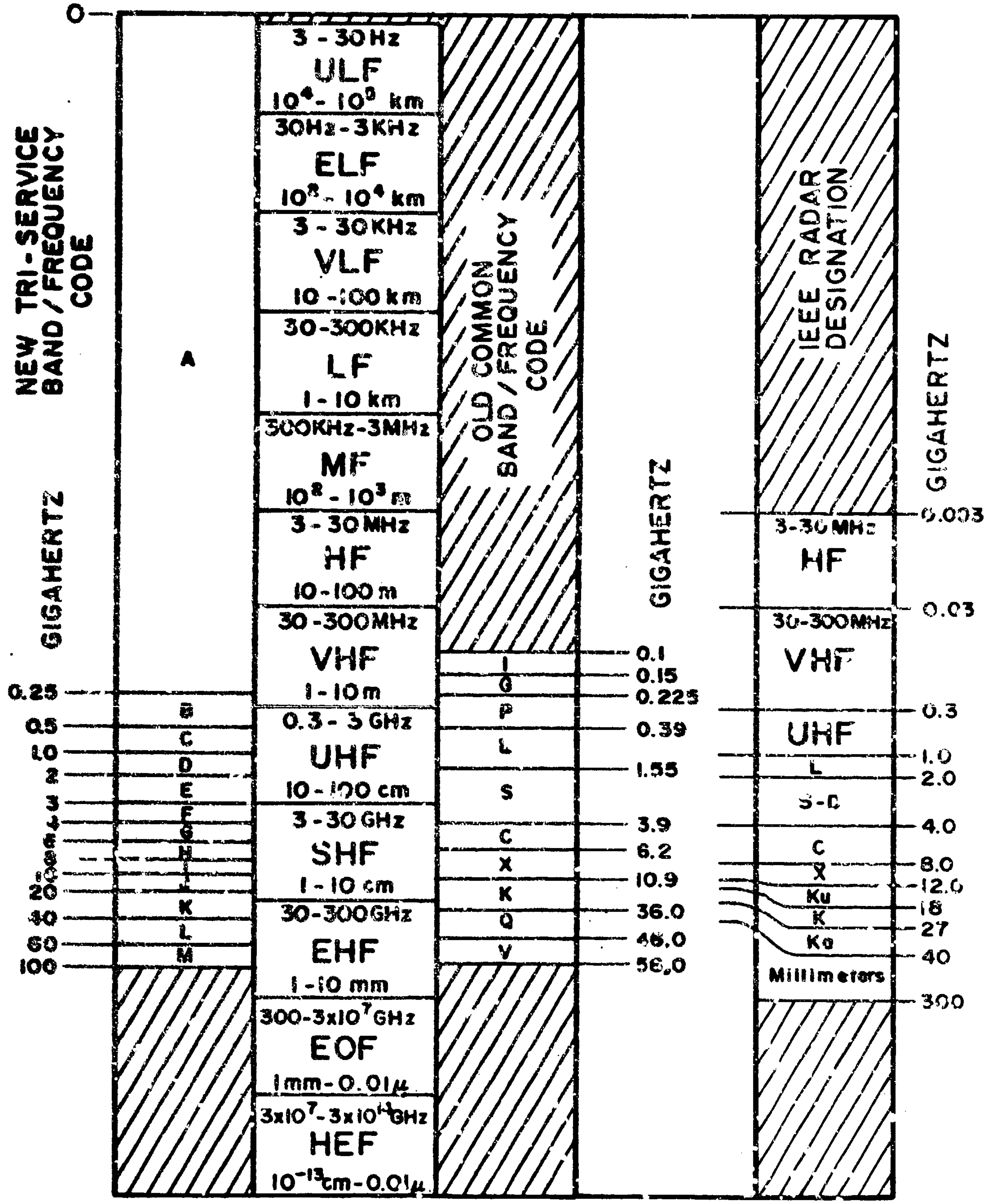


Fig. 29 ELECTROMAGNETIC SPECTRUM

and terrain, displays high levels of background noise from lightning, requires very large transmitting antennas, and exhibits very low propagation attenuation rates. All of these characteristics make ELF of primary value for strategic communications. Application trade-offs usually involve large geographic coverage, nuclear survivability, seawater penetration, high reliability, low information capacity, and major cost of transmitting antennas. Device technology is generally mature. A new potential exists with the application of superconducting Josephson junction magnetometers with receiving antennas. Experimental data is very minimal but well defined.

4.6.1.3 Very Low Frequency (VLF)

The VLF band runs from 3 to 30 KHz with wavelengths of 10 to 100 kilometers. VLF operations are characterized by low information bandwidth, moderate penetration into seawater, high atmospheric noise, and physically large transmitting antennas. This band is the primary means for long-distance communication to submerged submarines with other applications including radio navigation, and passive detection of manmade electromagnetic sources. Application trade-offs generally include nuclear survivability, connectivity requirements, information transfer rates, transmitting antenna cost, and geographic coverage. Others may be propagation accuracy and noise discrimination. VLF transmission is highly dependent upon the properties and disturbances to the ionosphere and also to the magnetosphere.

4.6.1.4 Low Frequency (LF)

The LF band runs from 30 to 300 KHz with wavelengths of 1 to 10 kilometers. This band is characterized by a rapid transition from the properties of the VLF band to properties of strong skywave absorption in the daytime, typical also of the next higher band, the MF band. Consequently, there is a large variability in propagation from day to night. The band below 60 KHz, for both application and propagation, is an extension of the VLF band with the major interest being strategic communications. Comments about VLF are generally true of LF. Application to LORAN, a radio navigation system, at about 100 KHz is of technical interest as a means for guidance and control.

4.6.1.5 Medium Frequency (MF)

The MF band runs from 300 KHz to 3 MHz with wavelengths of 100 to 1000 meters. MF signals are characterized by ground wave coverage during

daytime and long-range skywave at night. Night propagation is highly variable due to short duration skywave fades. Military use is limited due to heavy commercial use and full band occupancy. The AM broadcast band ranges from 555 KHz to 1,600 KHz. Wavelengths become commensurate with the physical size of large military targets which make radar feasible, although it is not actively used. Antenna size is small enough to put on movable platforms. Directivity for transmission is used in fixed installations. Applications other than communications and broadcasting tend to be of low practical value.

4.6.1.6 High Frequency (HF)

The HF band runs from 3 to 30 MHz with wavelengths from 10 to 100 meters. HF is characterized by heavy worldwide use in communications, mostly skywave supported. Other characteristics include extensive band crowding from primarily narrow band users, high variability in skywave propagation with high sensitivity to solar zenith angle and solar transient radiation, and frequent use of directive antennas. The HF band is the lowest band in which effects of the troposphere, sea state, and vegetation, such as a jungle, are significant. This band, which includes the highest frequencies that are ionosphere reflected, has been the backbone of military applications. It has been extensively explored for over-the-horizon (OTH) radar and communications. This band has been so heavily investigated that little effort is going into expanding its application. Most efforts are aimed at more effectively using this most busy part of the electromagnetic spectrum.

4.6.1.7 Very High Frequency (VHF)

The VHF band runs from 30 to 300 MHz and has wavelengths from 1 to 10 meters. VHF signals are characterized by line-of-sight (LOS), and extended LOS propagation, reasonable antenna size for moderate bandwidths, and sufficent bandwidth for high data rates and spatial resolution. Trans-ionosphere propagation becomes feasible, but ionization irregularities occurring primarily at auroral and equatorial latitudes can produce deep signal fades and large path deviations. Ionospheric and tropospheric refraction cause path bending which can produce significant angular offset. Ionospheric refraction is also dispersive. Tropospheric ducting due to inversion layers can be strong with signals being carried far beyond the horizon. Extraterrestrial and manmade noise are limiting factors on system sensitivity. This band has found wide application in communications,

navigation, radar, and consequently, passive detection. The FM and television broadcast bands are in the VHF r gion. FM broadcasts are in the band from 88 to 108 MHz, and television broadcasts span 54 to 88 MHz (channels 2-6) and 174 to 216 MHz (channels 7-13). Considerable advances in solid state devices and medium- and large-scale integrated circuit (MSI and LSI) technology have accelerated the development of VHF applications. Lowest equipment costs occur, as a general rule, in the VHF and HF bands. Trade-off considerations include range requirements, data rates, antijamming and anti-intercept needs, multipath effects, manmade interference protection, diversity options, and costs. Recent developments have been on satellite-to-earth communications links, antijam capabilities, adaptive array antennas, and new equipment to exploit the benefit of solid state amplifiers. Applications technology is considered relatively mature, and except for satellite communications applications, the level of technology has been rather low and is expected to further decrease. A driving force in this band is that as the technology matures and costs decrease, there is a trend to move the functions accomplished in this band to frequencies above 900 MHz. There is little application of signals in the bands to guidance and control of missiles.

4.6.1.8 Ultra High Frequency (UHF)

The UHF band runs from 300 MHz to 3 GHz with wavelengths of 10 to 100 cm. This band is characterized by properties very similar to those of the VHF band, with smaller physical size antennas and significantly increased bandwidth. Tropospheric propagation phenomena are pronounced as are the effects of terrain and sea state on multipath interference. The scintillation observed on trans-ionospheric propagation becomes considerably reduced with increasing frequency, but continues to be an important consideration. Ionospheric refraction becomes negligible above 1 GHz, but tropospheric refraction is still important. System trade-off decisions include electronic warfare threat, detectability, environment, data rates, diversity options, power, physical size, tracking coverage, reliability, and cost. Trends are for communications, navigation, identification, and surveillance applications to move upward in frequency with the consequence of considerable development of multiple use of communication, navigation, and identification taking place above 1 GHz. Interest in radar below 1 GHz is declining. The satellite navigation system, NAVSTAR Global Positioning System (GPS), and the Joint Tactical

Information Distribution System (JTIDS) are examples of these trends. Also starting in this band, the antiradiation missile (ARM) becomes a threat to radars with increasing frequency. Television broadcasts are authorized in this band over the frequency range of 470 to 890 MHz (channels 14 to 83), i.e., the UHF TV band.

4.6.1.9 Super High Frequency (SHF)

The SHF band runs from 3 to 30 GHz with wavelengths from 1 to 10 cm. This band is characterized by very wide available bandwidths, excellent angle resolution with reasonable physical size antennas, high transmitter power, mature technology below 12 GHz, and consequently, extensive utilization for all-weather surveillance, tracking, fire control, guidance, and the corresponding electronic countermeasures. Propagation characteristics include line-of-sight operation and increasing sensitivity to meteorological effects, with heavy rainfall attenuation approaching 3.6 db per km at 30 GHz. Atmospheric absorption becomes a significant factor for near-surface propagation above 12 GHz, reaching a relative peak of 1/8 db per km at 22 GHz. Tropospheric scattering, refraction, and ducting effects can be pronounced. Sea evaporation ducting becomes an important consideration above 3 GHz and can be particularly strong above 8 GHz, often extending radar or communications propagation to distances far beyond the horizon. Ionospheric scintillation, while greatly reduced in magnitude, often is comparable to link margins. Doppler effects become increasingly useful and a greater problem with increasing frequency for coherent systems. System trade-off considerations include bandwidth requirements, resolution needs, power, aperture, directivity, interceptability, and cost. Applicable technology development includes solid state power sources, microwave amplifiers, integrated circuits, precision frequency sources and synthesizers, electronically steered phase arrays, conformal array antennas, and multibeam low side lobe antennas. System explorations have included frequency agility, spread spectrum, and frequency hopping for low probability of intercept communications and antijam radar systems. Low probability of intercept radar using the 22 GHz or 60 GHz (EHF band) absorption bands; space-earth terminal communications links; space-to-space communications links; and imaging, radiometric mapping, and guidance systems have also been investigated.

4.6.1.10 Extremely High Frequency (EHF)

The EHF band runs from 30 to 300 GHz with wavelengths from 1 to 10 mm. Because of these wavelengths, this band is more popularly referred to as the millimeter wave (MMW) region. The nomenclature is further complicated by defining the MMW band from 30 to 100 GHz and referring to the 100 to 1000 GHz band as the near-millimeter wave (NMMW) region. The EHF band is characterized by emerging technologies, high atmospheric absorption, high attenuation in heavy rain and thick fog, large bandwidths, small physical size, limited apertures, low power sources, and limited propagation data base. Propagation windows at the low end of the band (30-40 GHz) and in the midband region (90-100 GHz) are finding more applications, with the 35 GHz region being used for systems in advanced development. The primary windows of interest across the spectrum are 35, 94, 140, and 240 GHz. The NMMW band represents a good compromise between the high resolution capabilities of optical radiation and the low loss propagation characteristics of microwaves. This portion of the spectrum offers significant additional advantage in that reduced scattering and narrow beamwidths will yield low probability of intercept operation and low vulnerability to jamming. Other system considerations for EHF include advantages of very small physical size, possibilities of using absorption to prevent intercept, very high available bandwidths, good spatial resolution using fairly small apertures, high Doppler sensitivity, limited support, expensive components, and unknown reliability. Current efforts consist of component and weapon device investigations, intercept receivers for intelligence applications, and development of radiometric and active systems for terminal guidance. Space-to-space and space-to-submarine links are also of interest.

4.6.1.11 Electro-Optical Frequency (EOF)

There is no agreed-upon standard for designating generalized frequency bands above EHF. Consequently, this report will define this band using terms that have become fairly well accepted in referring to electro-optical systems. The EOF band covers frequencies from 300 GHz to 3×10^7 GHz, with wavelengths of 0.1 cm to 1×10^{-6} cm. These wavelengths correspond to 1 mm or 1000 microns at the low frequency end and to 0.01 microns or 100 Angstroms at the high frequency end. The band covers five decades in frequency and, therefore, includes a number of spectral regions having various names. The sub-

millimeter band (300 to 3000 GHz), the upper portion of the near millimeter wave band (100 to 1000 GHz), the infrared (1000 GHz to 4×10^5 GHz), the visible (3.75×10^5 GHz to 7.5×10^5 GHz) and the ultraviolet (7.5×10^5 GHz to 3×10^7 GHz) regions are considered to be within the EOF band. There are no standard definitions regarding the limits of the bands/regions just listed. In fact, terms are used arbitrarily to refer to spectral regions within these bands that are ambiguous. Terms such as far infrared, long-wave infrared, mid-infrared, near infrared, near ultraviolet, far ultraviolet, extreme ultraviolet, and vacuum ultraviolet are used by various authors, with each one defining different limits for the same term. This obviously leads to misunderstanding and confusion, requiring either an accepted definition of terms or discontinued use of this terminology. It is recommended that a specific wavelength or range of wavelengths be stated when referring to this spectral region. This would eliminate the problem which currently exists and improve communications within the entire community.

The EOF band is characterized by high information bandwidth, very high spatial resolution, and highly variable absorption and attenuation by the atmosphere, fog, rain, dust, and smoke. Some of the windows for NMWW (360, 420, and 890 GHz) extend into the EOF band. There are primary IR transmission windows in the atmosphere at 6×10^4 to 1×10^5 GHz (3-5 microns) and at 2.1×10^4 to 3.8×10^4 GHz (8-14 microns), as well as over the visible spectrum of 0.4 to 0.8 microns. Ultraviolet windows exist from 0.34 to 0.39 microns and in a very narrow region slightly below 0.3 microns. The latter is limited to very short ranges. Ozone in the atmosphere absorbs all wavelengths less than about 0.3 microns.

Radiation in both the EHF and EOF bands is generated as unique active signals from manmade objects or machines. The e signals or signatures usually take on a characteristically different pattern from the background or clutter. Separation of these signals from the clutter is one of the major objectives of seekers used for guidance and control. The EOF band has been the primary band for fielded PGM systems, especially the laser semiactive terminal homing systems, IR guided missiles, and TV guided missiles. Technology supporting systems operating in this band are not only highly advanced, but have the potential for providing significant improvements through development of better sensors, detectors, integrated circuits, imaging techniques, advanced

algorithms for autonomous acquisition and reduction in size and cost of components. Trade-offs include target signature, frequency, range, countermeasures, weather, day/night operation, processing capacity, and system diversity.

4.6.1.12 High Energy Frequency (HEF)

The HEF band extends from 3 x 10^7 GHz to 3 x 10^{14} GHz with wavelengths of 10^{-6} to 10^{-13} cm. The lower wavelength is equivalent to one fermi and corresponds to the sizes of nuclei and particles themselves. This band is characterized by phenomena usually associated with high energy physics, thus, the name. Vacuum ultraviolet, X-rays, gamma rays, and cosmic rays are included in this band. The primary interest to guidance and control is the deleterious effects of spurious electromagnetic pulses and nuclear weapons effects on electronic components. Hardening is required against these effects and as possible counter-countermeasures to particle beams and directed energy weapons.

4.6.2 Other Sensing Regimes

In addition to sensing signals in the electromagnetic spectrum, there is also a capability to sense magnetic, seismic, and acoustic energy. The major application of such sensing techniques has been in the underwater area where a high degree of sophistication has been reached in sonar and hydrophones (acoustics) and in magnetometers. Ship and submarine detection as well as torpedo guidance and mine detonation employ these devices. Seismic sensors may be used to trigger target activated munitions by detecting characteristic vibrations produced by heavy armor. Progress is also being made in these areas for application to PGMs that operate above the surface. Magnetic field measurements may sense disturbances to the earth's magnetic field or actively generated electrical/magnetic fields produced by potential targets. Device technology has advanced to where equipment is sufficiently sensitive to operate at useful ranges and compact enough to be practical. The processing of acoustic signatures has advanced sufficiently to sort out particular signatures from background noise Because of false alarms, reliability, low signal-to-noise levels, and complexity, magnetic and acoustic techniques will probably remain a secondary mode in any future multimode, above the surface, sensing system.

4.6.3 Application to Guidance and Control Systems

There is not a perfect choice of frequency and sensor for use in the guidance and control of a PGM. The environment, target signature countermeasures, component state-of-the-art, size, cost, and complexity invariably lead to trade-offs in some aspect of the system. Consequently, from the very beginning, arbitrary choices must be made based upon the latest available or predicted technology. Once these choices are made, the shortcomings and vulnerabilities of each system soon become visible. Current trends indicate that most PGM sensor developments will come from the SHF, EHF, and EOF frequency bands.

4.7 Environment Sensing Guidance

In environment sensing guidance, a PGM, while in flight, obtains information on its own absolute position from some external source other than the launcher (fire-control equipment) or the target. The PGM then uses this update of its position to adjust its flight path, if necessary, to hit a preselected target. Inertial guidance is generally used to control the missile between updates. In order to accomplish environment sensing, the electromagnetic spectrum, as just described, is used in some way or other. One approach is to have an on-board star (celestial) sensor which is used for a navigation update. This has generally been associated with exoatmospheric missiles and has been too expensive for incorporation into a tactical PGM. However, continued research in this area may make such a system affordable in the future. A related technique would be to use a satellite system such as NAVSTAR-GPS for a position update. A more popular, and potentially less costly, method is to have some type of map stored within the PGM that is made during prior reconnaissance. This reference may may be on film or digitized (converted into an electronic signal) for storage in a computer and ease of comparison with real time data obtained during the missile's flight. Because of the large amount of information in the reference maps, a very large computer storage capacity is required for digital storage. With a radar map and a radar sensor, a periodic comparison of reference scenes can be used to determine missile position during flight. This approach is called Radar Area Correlation (RAC or RADAC) or Radar Area Guidance (RADAG), and when applied in a passive mode at MMW frequencies is called Microwave Radiometry (MICRAD). RADAG is being employed for terminal guidance in the PERSHING II missile.

Optical photos/maps may also be employed as position references. They are compared to scenes obtained during a missile's flight to update the inertial guidance system or to provide terminal guidance. One system using this approach is known as Digital Scene Matching Area Correlator (DSMAC), and is intended for use in cruise missiles. Another variation on this theme is to use radar to measure the contour of the land over which the system is flying and make a comparison with stored contour data. This concept is used in the cruise missile and is called Terrain Contour Matching (TERCOM). Generally, environment sensing guidance is used for systems with a range greater than 300 km, where precise terminal guidance is required and an accurate midcourse update is needed to assure the desired CEP. Otherwise, the added cost and complexity cannot usually be justified.

4.7.1 Matcher/Correlator Guidance

One approach to autonomous target acquisition that is possible against fixed tactical targets is image correlation or map-matching as mentioned above. As a result of prior reconnaissance, a map of the target area is made and processed to mark targets. A version of this map is then stored onboard the missile in a computer. As the missile flies along, it uses a sensor similar to the one used to generate the map to take a live image to compare to the stored image. If an exact comparison is made, the missile can fix its position.

Four error sources must be considered in designing matcher/correlation systems: geometrical distortions, systematic intensity changes, quantization errors, and possible enemy jamming. Geometrical distortions, in turn, result from four causes: synchronization, rotation, scale factor, and perspective. These difficulties have been overcome sufficiently to be used in the cruise missile as DSMAC (Digital Scene Matching Optical Correlator) and TERCOM (Terrain Contour Matching) and in the PERSHING II missile as RADAG (Radar Area Guidance).

Success with matching/correlation and advances in technology are developing into another popular guidance concept, imaging infrared. In this case, instead of having a stored map, the missile has a built-in algorithm for feature extraction that will permit target recognition and autonomous acquisition. There is intense activity in this area for application to future missile guidance systems.

4.7.2 Terrain Contour Matching (TERCOM)

Terrain contour matching is a form of correlation guidance based upon a comparison of the profile of the ground (terrain) over which a missile or aircraft has flown, with prestored data taken on the profile or contours of the same area. Obtaining the reference data requires prior measurement of the ground contour in areas of interest. This type of guidance is used for updating a midcourse inertial guidance system on a periodic basis and has been applied to the guidance of cruise missiles, which usually fly at subsonic speeds and fairly constant altitudes.

As the missile flies, it measures the variations in the ground's profile using a radar altimeter. These variations are digitized and processed for input to a correlator for comparison with the stored data. Through this process, the missile can determine its position and correct any errors that have developed since the previous update. Figure 30 illustrates the basic concept employed by TERCOM. The terminal guidance stage may be based upon the final TERCOM update and a preprogrammed course relying on the inertial system, or a separate terminal homing seeker may be employed that can recognize the target and provide the final guidance commands.

In order for such an updating technique to perform properly, there must be sufficient variation in the terrain to generate a usable signal. Obviously, such a system will not work over water. It probably would not work very well in the midwest, where the ground is very flat. Therefore, some consideration must be given to the terrain surrounding the target when employing this type of guidance. The data collected for the reference map will provide the information necessary to predetermine if the system will work in the areas of interest.

4.8 Signatures

Three items are circled in Figure 1: Signatures, Simulations, and Countermeasures. Each of these three items is important for the development and fielding of a PGM. Signatures will be discussed in this section. The other two items will follow in subsequent sections.

The ultimate test of any PGM is to hit the target it was meant to hit. In hitting the target the PGM has accomplished the most critical act of its mission. It has fulfilled its raison d'etre: deliver the payload. To

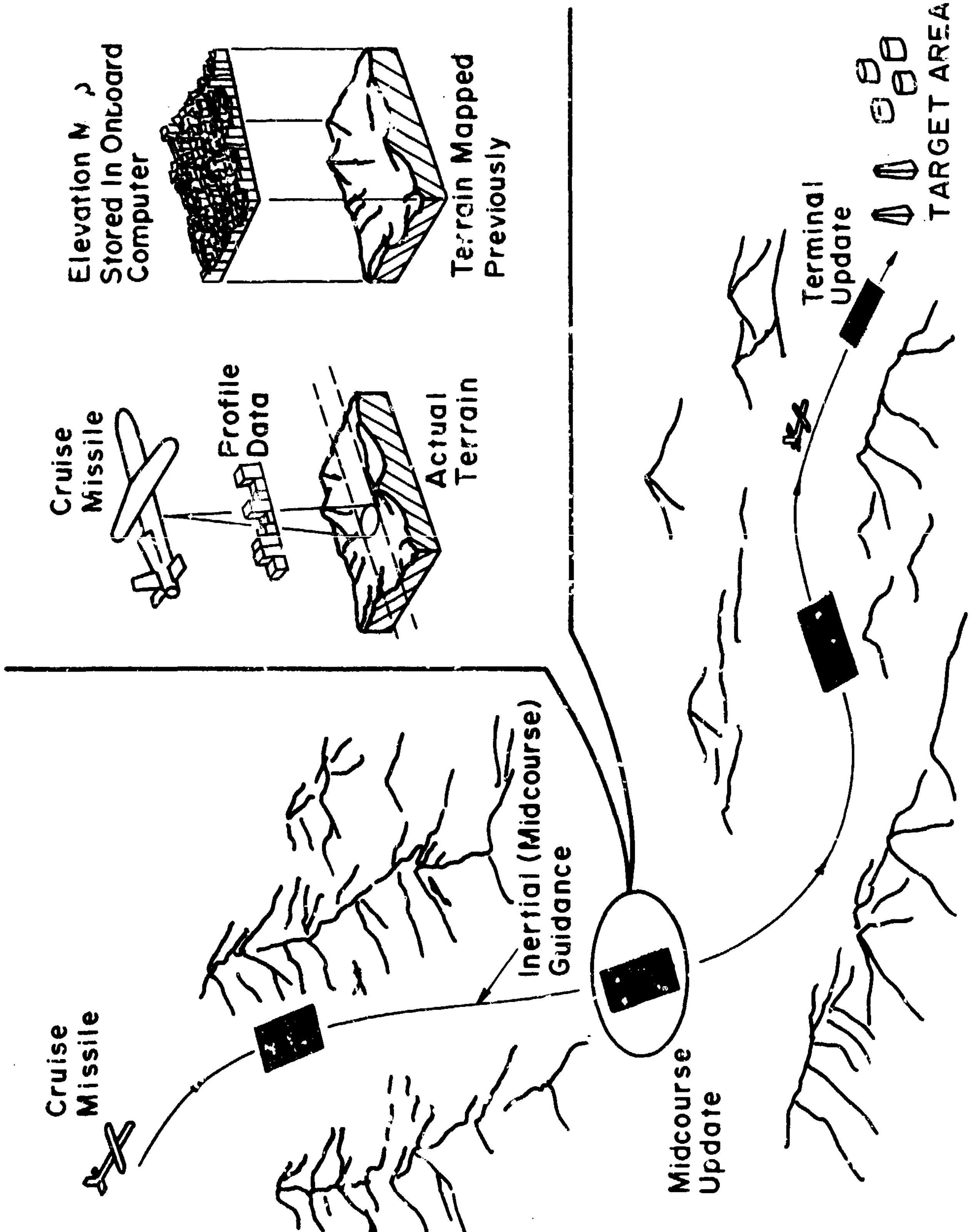


Fig. 30 TERRAIN CONTOUR MATCHING

accomplish its objective, the PGM must pick out the target from all of its background clutter. Like searching for a friend in a crowd, the PGM must have some awareness of what it is looking for. The characteristics of a target must be as recognizable to a PGM as the image and features of a friend. These unique characteristics of a target are its signature. A PGM must be able to distinguish signatures just like a handwriting expert. The process of recognizing target signatures, however, is not as advanced as graphology. The target signature community is trying to cope with three basic problems: standardization, adverse environments, and autonomous acquisition.

4.8.1 Standardization

There are two schools of thought about measurement and standardization of target signature data for use in designing PGMs. Both sides have some strong points which will be stated without taking sides.

There are those who state that it is not possible to standardize target signature data. Universal data bases are not realistic. There is a need to measure target data for every system development to fulfill the specific needs of the program. New seeker concepts demand new signature data. General measurement programs record data from broadband instrumentation, but seekers are narrowband. A lot of signature data is taken, but comparatively little is reduced and analyzed (possibly only 5-10 percent). Data collectors are not necessarily data users. The collectors do not know the type of target/background signature data required by seeker designers and cannot anticipate the types of data required by designers of future seekers.

On the other hand, there are those who state that a standardized, central signature data base is needed. More than this, a battlefield signature model should be developed. Based upon such a standard model, it would be possible to better achieve a definition of signature variables: world wide measurement effects atmospheric attenuation, seasonal and diurnal variations, variations in background clutter, target contrast, signal processing, data recording, data storage, and modeling. Otherwise, most of the possible signature data taken for a specific system is lost. Instrumentation variables are introduced where the characteristics of the instrumentation used to take signatures become part of the signature. Data is processed for specific needs so that it is of little or no value to others. There is a need to take data with minimum processing so that characteristics of interest are not lost in the processing.

This controversy will probably result in a compromise. The designers of PGMs ultimately have to test their hardware in a real world environment where signatures have a go, no-go impact. The measurers of signatures may be more aware of the variables involved and the instrumentation limitations. In addition, there are alternate users of the same or similar signature data. Target surveillance, acquisition, and tracking components of fire control systems also need signature data. Furthermore, signature data bases may be valuable for developing simulations, countermeasures, or counter-countermeasures. Data collectors and data users may have different interests, but there is also a coupling between the two. The degree of this coupling will be receiving closer management attention in the future.

4.8.2 Adverse Environments

One of the current thrust areas in the development of PGMs is to improve the capability of operation in adverse environments. An adverse environment as used here is generally related to the weather, day-night variations of signatures, or battlefield smoke/debris. Other environmental effects might include heat, cold, snow, sand, rain, etc. These factors degrade the operation of the guidance system by interfering with its ability to "see" the target, i.e., target signature and energy propagation variations. Just as darkness, fog, or smoke hinder a human's ability to see, similar factors affect the sensors employed by PGMs. In order to minimize these effects, sensors that employ different parts of the electromagnetic spectrum are used. Although radiation in the visible region may not penetrate a smoke cloud, infrared or millimeter waves may. Thus, by selecting a different spectral region of operation, systems can sometimes be designed to provide operation in the desired environment. However, there are tradeoffs in the characteristics of the different sensors that must be considered because they impact directly on the capability of the guidance system to perform the desired mission.

Each type of sensor has specific characteristics that make it attractive for the particular guidance concept being pursued, making substitution impossible. Therefore, although an adverse environment for one type of sensor may not degrade the operation of a different type sensor, it is not generally feasible to make simple changes in the design to solve the adverse environment problem. This partially accounts for the many different technology programs

that must be conducted in order to develop a system(s) that fulfills all of the requirements.

Three other questions need to be answered. To what extent can a PGM's operation be degraded by an adverse environment and still be acceptable? How often is the adverse environment expected? Finally, exactly what is meant by an adverse environment?

The reason for the interest in adverse environments is that different sensors are affected in different ways. For guidance systems requiring the highest precision, optical or infrared techniques have been developed. However, these systems can become unusable due to rain, fog, clouds, or smoke. To provide operation under these adverse conditions, reliance must instead be placed on radar, which is not generally obscured by these conditions.

While the conventional radar bands, e.g., C or X bands, have long been used for guidance, use of higher frequencies (e.g., millimeter waves) makes possible the use of smaller components, such as the antenna in a missile seeker. Conversely, for a given size antenna, the higher frequencies provide greater antenna gains and narrower beams, thus improving the resolution and perhaps precision of the guidance system.

The propagation loss in the millimeter waveband is highly dependent on frequency. In order to obtain usable signal strengths for the required missile-to-target ranges, it is usually important that millimeter wave guidance systems operate in one of the windows having lower atmospheric attenuation; namely, those bands centered around 35, 95, 140, or 220 GHz. The lower bands are desirable from the viewpoint of lower propagation loss; the higher bands, because of improved resolution. In the presence of rain the attenuation increases in all bands, and the two lower windows (35 and 95 GHz) shift downward in frequency, slightly below the clear-weather windows.

Electro-optical systems sense electromagnetic radiation which is transmitted through the atmosphere from a target. The radiant energy may be reflected from the target or may originate there as a target thermal signature. Not all target energy will reach the sensor because of attenuation by the atmosphere. A characteristic of the energy which will determine if it is attenuated by the atmosphere is its wavelength. Normal atmospheres, for example, attenuate most energy at wavelengths of 1.5-3 microns and 5-8 microns

due to the water vapor and CO_2. This attenuation is so severe that only "windows" on either side of these wavelengths, i.e., 3-5 microns and 8-12 microns, are considered for infrared sensors.

When other than the normal atmosphere is considered, additional attenuation of energy transmission may occur. The attenuation may be a result of absorption of the energy, as might occur due to either gases, vapor or particulate materials in the atmosphere, or it may result from scattering or diffusing of the energy as it strikes particles. The amount of attenuation, whether it is a result of scatter or absorption of the energy, is determined by the amount of the material present in the atmosphere and the length of the path between the radiant energy source/reflector and the sensor.

The amount of attenuation of energy of a given wavelength by an airborne particulate material (aerosol) is also determined by the specific material and particulate size of that material. This property of the material of a given particle size is termed its extinction coefficient for a given wavelength. Extinction coefficients for a material change for each wavelength of energy transmitted through them. Generally, shorter wavelengths of energy (i.e., visible) are attenuated more than longer wavelengths (i.e., far-infrared/thermal) when passing through an aerosol.

Figure 31 illustrates the atmospheric attenuation experienced by electromagnetic waves for various conditions. The dashed curves given average values.

The characterization of adverse environments becomes a very complex interaction of many variables. Seeker wavelength, bandwidth, power output, receiver sensitivity, and field of view are parameters of the PGM. Extinction coefficient, attenuation, aerosol particle distribution and density, temperature, wind, humidity, barometric pressure, and altitude gradients are atmospheric contributions. Add to the environment, dust, electromagnetic pulses and other nuclear effects, countermeasures, chemicals, explosive by-products, and maritime influences, and the problem is only resolvable by a specific statement of what is meant by an adverse environment.

4.8.3 Autonomous Acquisition

Automatic tracking after acquisition (lock-on) is a mature technology for many types of sensors. By using lock-on before launch, the guidance system

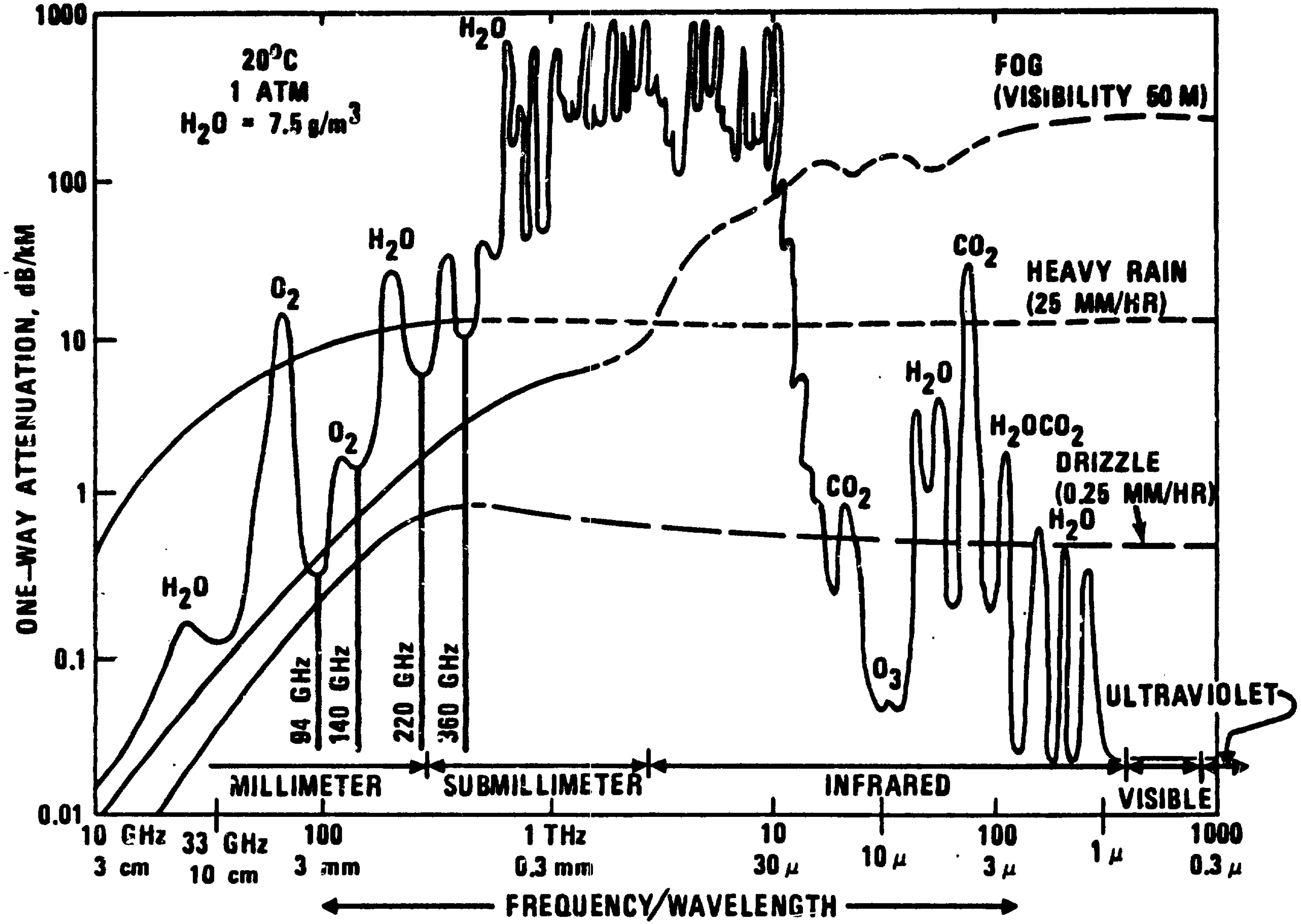


Fig. 31 ATTENUATION BY ATMOSPHERIC GASES, RAIN AND FOG

can be simplified. In some cases it is not possible for the system to lock-on before launch, but conditions are such that lock-on after launch is relatively easy, i.e., the target is in the antenna beam and is the only target available in a clutter-free environment. Some radar guided missiles are designed to operate in this mode. Autonomous acquisition, on the other hand, requires a more complex lock-on after launch procedure, and generally implies a true area/volume search, automatic target recognition, and acquisition.

The most difficult mode of operation for a PGM is post-launch autonomous acquisition, where a projectile or missile is fired into a general target area and upon entry to the terminal phase, searches for, recognizes, and selects a target without operator assistance. This is synonomous with the auto-cue problem, but is generally confined to the air-to-ground scenario. Autonomous acquisition has been associated with image processing, however, other types of signatures may also support its implementation. The techniques employed in general image processing approaches can be grouped into five classes: (1) image enhancement, (2) segmentation, (3) feature extraction, (4) feature classification, and (5) correlation.

Image enhancement deals with a broad class of image processing operations whose objective is to convert the input image data into a form more suitable for further processing. This can include noise elimination, geometric correction, spatial filtering, or amplitude spectra modification. These operations can be carried out in either the spatial domain or in a variety of transform domains, such as Fourier, Haar, Hadamard, etc. The term "more suitable" implies that enhancement techniques differ in accordance with the image data processing operations that follow, and hence, are a function of the specific application. However, commonality can exist between applications.

Segmentation deals with isolation of potential features or areas of an image from what is otherwise considered background. A major element of this class of operations is edge extraction, which is employed to isolate or define objects. Edge extraction can include processing which enhances feature boundaries and subsequent thickening or thinning operations which attempt to provide a continuous line describing the feature boundary. While the edge extraction step is, in general, a prelude to feature classification, it can also be used to precede correlation steps in which the binary feature boundaries are correlated instead of area correlations of pixel amplitudes.

Feature extraction is the process by which characteristics of the segmented features are determined. Characteristics can include areas, perimeters, area-to-perimeter ratios, and various other geometrically sensitive parameters. Other types of characteristics utilized to describe image features may include texture or may even include the entire segmented portion of the image, for cases where template matching is employed for feature classification.

Feature classification consists of matching the extracted features of segmented objects to a set of known or desired features of a target object for the purpose of identifying the type or class of object appearing in a scene. This can consist of correlations of the segmented object with a prestored target template, or if dealing with geometrically derived features, can consist of a probability of match score of the input object with prestored target feature profiles.

Correlation deals with the mathematical correlation of a reference and input image or image segment for the purpose of determining if a precise match exists or the best match for the relative positions of the two images. This can be accomplished using either picture amplitude or phase information, threshold or binary image information, or picture edge information. It is possible to make a scene-to-scene correlation with Bayesian statistics to educate the seeker. In the case of map-matching for midcourse or terminal guidance, correlation can be performed on the picture as a whole, or with multiple subareas. When it is performed on segmented objects, it is essentially template-matching for feature classification.

Any of these image processing techniques, if successful, must be able to work in ideal weather and environmental conditions as well as conditions where the target signatures are degraded.

4.9 Countermeasures (CM/CCM)

The purpose of countermeasures (CM) is to cause a smart weapon to do dumb things. The dumbest thing that a smart weapon can do is to miss its intended target or detonate before it reaches it. The enemy may try to generate false target signature information or may try to cause the missile to break lock. The use of chaff, flares, or smoke aerosols are significant countermeasures when they are used to break one of the links either between the missile and

the target or between the missile and the target launcher. It is the increase in the sophistication of countermeasures which is driving the designers of PGMs to consider multimodes in their operation.

Whenever a weapon system is built and fielded, the enemy would like to reduce the effectiveness of that system. Defenses are improved to counter new offensive systems. These improvements or capabilities to reduce the effectiveness of weapons are called countermeasures. Countermeasures may include chaff or electronic jamming (ECM) against RF PGMs, flares against IR PGMs, or new armor to defeat the warheads of PGMs. After a countermeasure has been taken by the enemy to reduce the hit probability or kill probability of a PGM, methods are sought to defeat the countermeasure. These new efforts are called counter-countermeasures (CCM). Electronic counter-countermeasures (ECCM) may be employed to reduce the impact of jamming on RF PGMs, a dual color or dual mode IR PGM may be developed to defeat flares, or a new warhead may be designed to defeat new armor.

One of the recent developments in this area that has received considerable publicity is stealth. The idea of stealth is to make an attacking airplane or missile invisible to enemy radar by reducing its radar cross section through special shaping, the use of radar absorbing coatings, and/or the employment of nonconductive materials in its construction. This is not an easy task, since radars operate at many different frequencies and radar cross section is somewhat dependent on frequency. Radar detection range is also related to the fourth root of the radar cross section. In other words, the cross section must be reduced by a factor of sixteen (16) for each halving of the detection range.

Paints have been used to reduce the visual detectability of targets for many years to minimize the reflection from the sun and to decrease the contrast with the sky or ground. Combat aircraft may have their tops painted in a camouflage design or dark color and their bottoms painted light blue to reduce their visibility as a form of countermeasure. Combat vehicles are usually painted an olive drab color or camouflage design to reduce their visibility. Efforts have also been devoted toward reducing the infrared radiation from the hot areas around the engine exhaust on helicopters and tanks as a countermeasure against infrared guided missiles. This is known as target signature suppression.

People in the CCM business are frustrated by the difficulty of having CCM features incorporated into initial weapon system designs. Logic and time will never allow resolution of that issue. A weapon is frozen in design to meet a given threat. It takes time to build a weapon system. The threat changes over that time by incorporating countermeasures. Development may be extended to incorporate appropriate counter-countermeasures, or product improvements may be made to the fielded system. Sometimes the development of the system may be stopped altogether because a new countermeasure has made the whole system obsolete before it was fielded. Then, everything starts all over again.

4.10 Simulation

Simulations are being used more and more to evaluate concepts and designs, eliminate trial and error in captive or range flight tests, reduce costs, reduce false starts in missile development, eliminate development redundancies, shorten development time cycles, substitute for flight testing, minimize flight test failures, and train operators. The cost of consumable hardware is so high that nondestructive simulations are the only viable option to hands-on experience.

The first step in the development of a weapon simulation is to generate a mathematical model describing the performance of the weapon system in its environment. The performance of each component or unit of the system is defined mathematically. The overall model must include all system functions and their interactions. One such model is shown in Figure 32. This model parallels closely the discussion on components in Section 3. Note, also, that the primary objective of the model is to steadily decrease the difference between the target position and the missile position, $\underline{R}_T - \underline{R}_M$.

The usefulness of a model of any system is dependent upon the identification of the independent and dependent variables which influence the performance characteristics of the item in the real-world environment. The value of any model is also interdependent upon the system parameters. In a guided weapon system, these elements may consist of system geometry, size, weight, balance, gravity, thrust vectors, environmental effects, stability, inertia, vehicle configuration, launch dynamics, maneuver capabilities, or high-g effects. These characteristics must, in the model, be realistically represented in order to simulate the concept in optimized form.

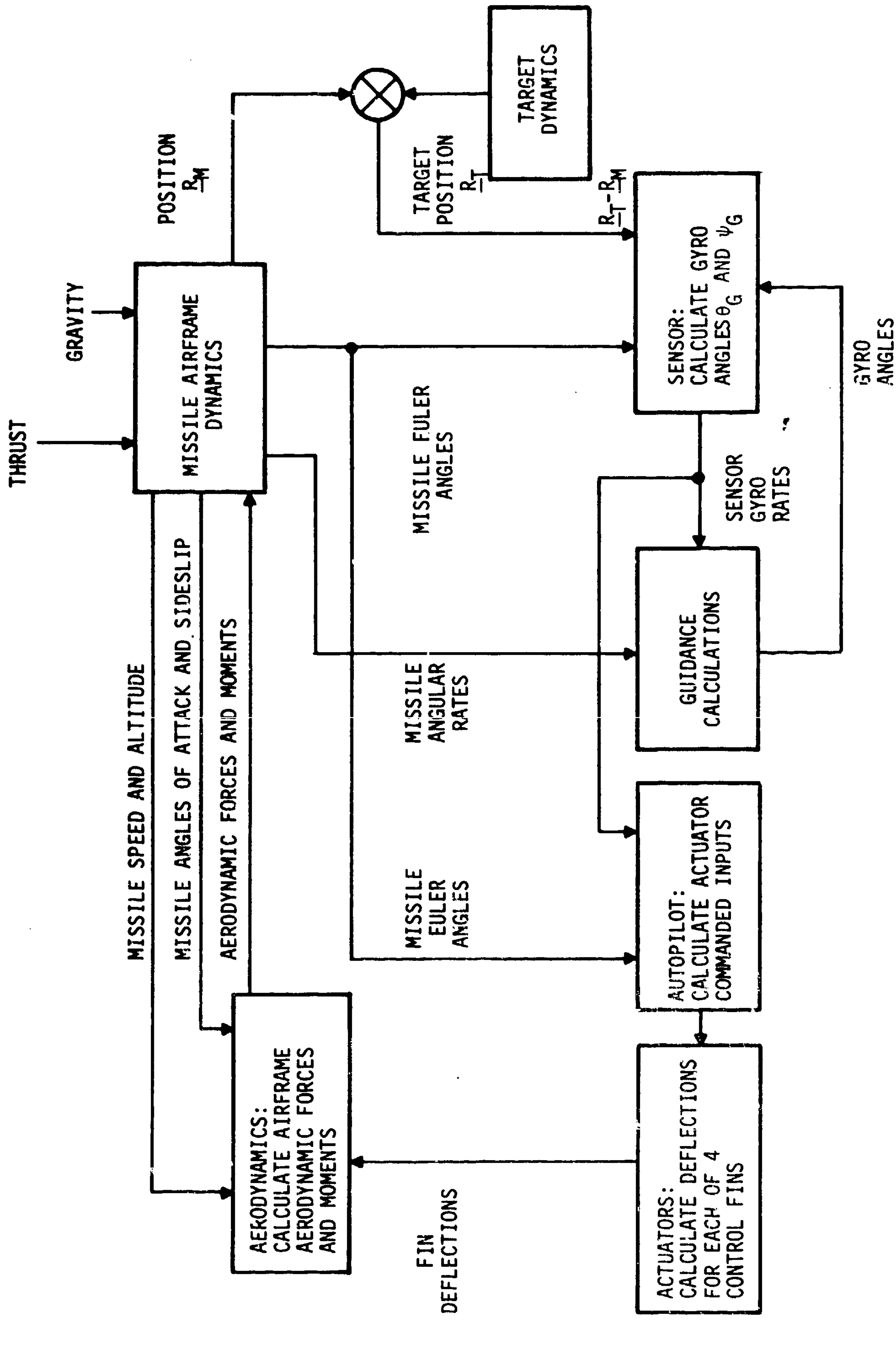


Fig.32 OVERALL MATHEMATICAL MODEL OF A MISSILE SYSTEM

The next step is to develop one of three types of simulations. One type is a computer simulation based upon an analog, digital, or hybrid computer. Another type could be a physical effects simulation. The third approach, which is possible with development of some of the missile's components, is a hardware-in-the-loop simulation. One or more components, as well as the full guidance and control package can be used in this approach. In the latter approach, or the others, a man-in-loop may be included in the simulation. In all of these cases, the simulation is exercised to determine system performance and/or shortfalls under various combinations of operating conditions.

4.11 Accuracy and Kill Probability

In discussing the reason why smart weapons are being developed, the fact that they are generally more accurate than dumb or unguided weapons was emphasized. The accuracy of a guided weapon depends upon a large number of factors, and although every effort is made to make the guidance systems as error free as possible, not every smart weapon fired will hit and/or kill its target. Many of the errors experienced are of a random nature, resulting in a miss distance probability distribution for any given target. Some of the factors that determine this distribution are the following:

- ratio of maneuverability of the missile to that of the target
- ratio of the missile to target speed
- dynamic characteristics of the missile guidance system
- target tracker/seeker noise
- saturation levels of the guidance system
- system biases
- launching dispersion
- number of targets and their formation
- launch range and target aspect angle.

For each specific type of target, a weapon will exhibit a kill probability versus miss distance distribution that is dependent upon at least the following factors:

- missile-target relative attitude at intercept
- warhead characteristics
- fuzing system characteristics and operation
- altitude

- vulnerability of the target's various components/ crew to the weapon's warhead

As one can imagine, to assemble factual data on all of these factors is a tremendously complex operation and very costly. As stated in the previous section, simulation can provide a tool for relating many of these factors to missile accuracy and kill probability in a cost-effective manner, accounting for the increased use of simulation in all areas related to smart weapon development.

In order to establish a basis for comparing and discussing accuracy, a number of measures of accuracy have been generated that are based upon statistical theory. Experience with guns, gunfire control systems, radar, and guided weapons has shown that the distribution of errors about the target or aim point is generally random and follows a normal frequency distribution. This distribution forms the basis for much of the theory of probability and is covered in many texts. It is applicable to many branches of science and engineering dealing with random variables and has been employed in solving many military problems, as well as being associated with games of chance.

The normal frequency distribution of a single variable about zero is illustrated by the bell schaped curve shown in Figure 33. This curve is known

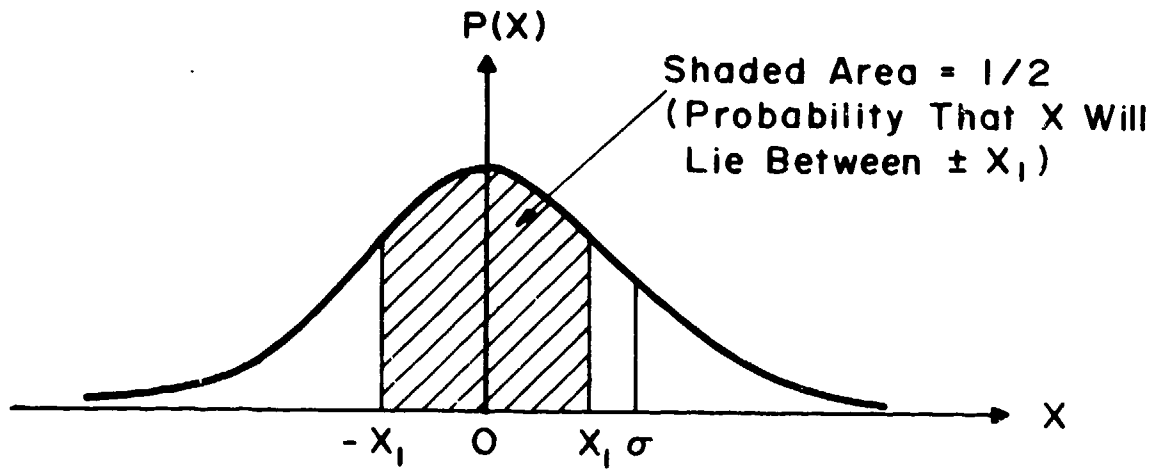


Fig. 33 NORMAL PROBABILITY FREQUENCY FUNCTION

as the normal or gaussian probability frequency function or normal probability density function. It is generally normalized so that the area under the curve equals unity. This allows the probability of any range of values along the abscissa (x axis) to be calculated by determining the area under the curve between the values of x of interest. For example, suppose that a very large (theoretically infinite) number of missiles were fired at a target and the miss distances in a single plane, say up/down, were recorded and plotted, where the miss distance is plotted along the x axis (misses above the target as +x and misses below the target as -x) and the number of misses having the particular value of miss distance plotted vertically parallel to the p(x) axis. A curve similar to that shown in Figure 33 would be obtained. Once this data is obtained, it is possible to discuss the various terms related to accuracy. By definition, the probable error is that value of ±x that contains half of all the errors. This is shown by the shaded area in Figure 33, where x_1 is the probable error. Another term frequently used in probability theory is the root-mean-square (rms) error, usually referred to as σ. This is also known as the standard error or standard deviation, and is equal to 1.4826 times the expected error. Whereas the probability was 50 percent that a given missile would have an error less than x_1, the probable error, the probability is 68.3 percent that it will have an error of less than σ. The standard deviation is useful in calculating other statistical parameters that will not be discussed here.

In practice, the two dimensional case is of more interest than the one dimensional case just discussed because it allows accuracy to be specified in two directions, i.e., up/down and right/left, as in target shooting. Again, if the errors are random with no fixed or bias errors, the normal probability frequency function can be developed for the two dimensional case, centered at the origin (target). The probability functions are not necessarily the same in each dimension, but in many cases they are, resulting in symmetrical probability frequency functions centered about the origin. This is illustrated in Figure 34. Now it is possible to talk about circles of equal probability, where the probability of an error being within a given distance of the origin (target) can be calculated.

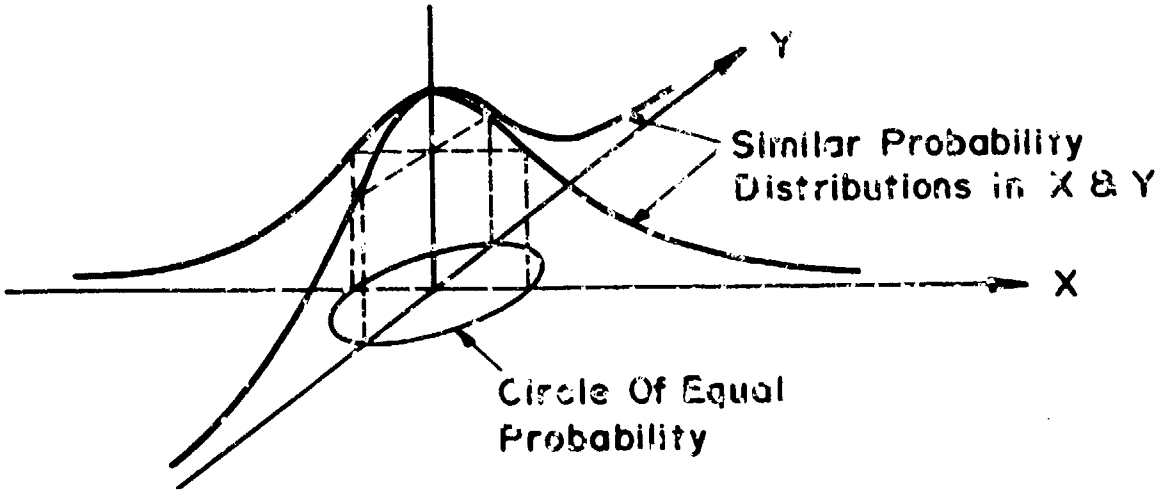


Fig. 34 NORMAL PROBABILITY FREQUENCY FUNCTION IN TWO DIMENSIONS

The circular error probability (CEP) sometimes called circular probable error, is defined as the radius of a circle centered at the target within which 50 percent of the radial errors are contained. This assumes that there are no mean, average, or bias errors present. A missile has a 50 percent probability of being within the CEP at intercept. The lower the CEP, the more accurate the missile. When the CEP is on the order of the size of the target, the missile has a 50 percent probability of hitting it. The use of CEP in defining accuracy has been associated with surface targets, stemming from artillery projectile or bombing accuracy. Precision guided munitions have gotten their name from the improvement in CEP, obtained through advances in guidance and sensor technology. The CEP is one major indicator of the intelligence quotient (IQ) of a smart missile; but the complexity of the task must also be considered in the process of assigning IQ. It might be said that the lower the CEP, the smarter the missile, for a given task. The smarter the missile, the more precise the guidance and control. Consequently, the interchangeability of the terminology of smart weapons and precision guided munitions is reached. Generally then, a PGM must have a 50 percent or greater probability of hitting the target. Hitting the target may also mean that the CEP is less than the lethal radius of the PGM warhead.

The accuracy of a missile is also often expressed in terms of miss distance, when discussing air targets. Although rarely defined, what is usually meant is the root-mean-square (rms) miss distance which is equal to the standard deviation (σ) of a normal distribution in two coordinates, x and y.

Although the error statistics in these coordinates are independent, under most conditions the value of the standard deviation in one coordinate is likely to be similar to that in the other coordinate, leading to consideration of the accuracy in terms of a circular distribution as stated above. Making this assumption, statistics indicate that a missile has a 39.3 percent probability of coming within the stated miss distance of the target. It follow that a missile has an 86.5 percent probability of coming within twice the stated miss distance (2σ) and a 99 percent probability of coming within three times the stated miss distance (3σ) at target intercept.

The CEP is related to miss distance by the factor, 1.177, the CEP being the larger. In other words, given the CEP, the miss distance can be calculated by dividing by 1.177, or given the miss distance, the CEP can be calculated by multiplying by 1.177.

Dispersion is another term sometimes used to express missile accuracy. The dispersion is defined as the diameter of a circle, perpendicular to the median trajectory, within which 75 percent of all the missiles would pass if a large number were fired at the same target under the same conditions. However, this term may also be used to refer to the general distribution of errors about the target, so care must be taken in interpreting its exact meaning.

Figure 35 may help visualize these two dimensional measures of accuracy. A hypothetical plane is drawn through the target, and the various measures of defining accuracy (CEP, miss distance, and dispersion) are shown together with the probability of an intercept being within their boundary.

Sometimes the CEP is measured in mils, where one mil is one-thousandth of the distance from the launcher to the target. For example, a missile with a CEP of 3 mils would have a 50 percent probability of hitting within a circle 30 meters in radius about a target at 10 kilometers (0.003 times 10,000 meters). This measure of accuracy appears to be associated with gunnery, where angles are measured in mils (6,400 mils equals 360 degrees) and firing tables are annotated in mils.

If a missile does not have a symmetrical error distribution, then equal probability ellipses can be used to describe its accuracy. In such cases, conversion formulas have been developed to relate the areas in such ellipses

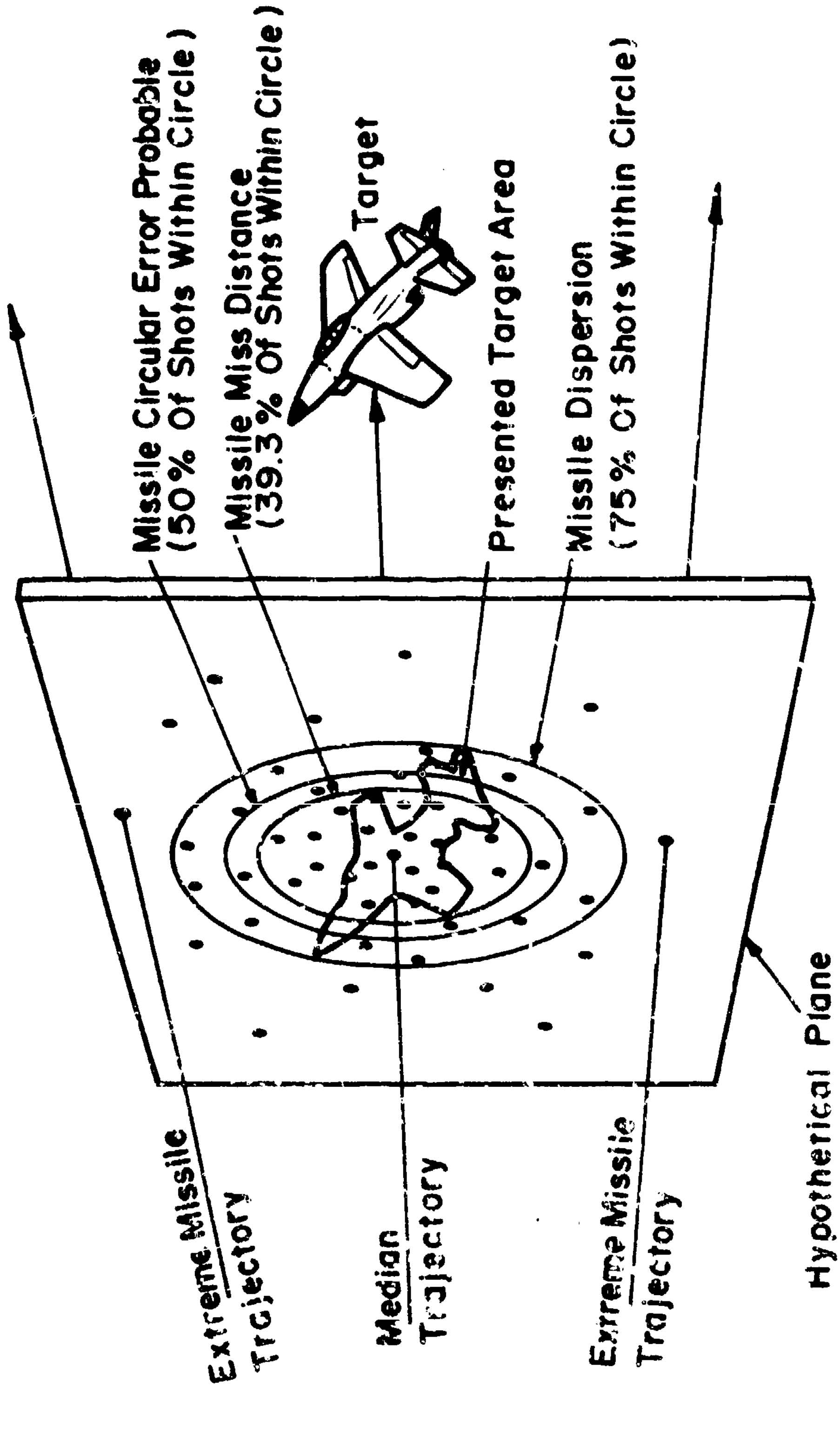


Fig.35 DISPERSION OF ERRORS ABOUT TARGET

to a circular area, so that the accuracy can be expressed in terms of circular error probable. However, this could be misleading in cases of large ellipticity.

Sometimes when discussing airborne or undersea targets, three variables are necessary to describe acuracy, leading to three dimensional normal distributions, where surfaces of equal probability have ellipsoidal or spherical shapes. This can be appreciated when considering the timing of the warhead detonation. The detonation occurs along the trajectory and the exact timing of detonation can be defined by a normal probability frequency function along the z axis. If all three probability distributions are similar, equal probability spherical surfaces can be identified. As in the one and two dimensional cases, the radius of the spherical surface containing 50 percent of all the errors is known as the spherical probable error. Because of the complexity, the three dimensional case is not widely used.

Some missiles are required to hit the target to be effective due to their warhead design. This is the case for shaped charge warheads and other penetration type warheads (kinetic energy) used against hard targets, i.e., armored vehicles, bunkers, or ships. It may also apply to airborne targets when the missile does not have a proximity fuze and must impact the target to explode the warhead. Here, accuracy is sometimes stated in terms of probability of hit for a given target area and range. The higher the probability of hit, the greater the accuracy of the weapon system.

Based on this discussion, it should be obvious that a statement of a weapon's accuracy can be very ambiguous unless the terms and units are carefully defined.

As mentioned, kill probability depends upon a large number of factors, one of which is accuracy. The greater the accuracy (smaller the CEP), the greater the kill probability.

What is meant by kill probability? There are a number of different types of kills that can be defined depending upon the degree of damage to a specific target or upon the outcome of the target's mission. These are given different identifiers by different authors, so again, care must be taken in defining terms when discussing kill probability.

A K-kill is a complete kill, i.e., an aircraft falls out of control immediately or a tank, ship or bridge, etc. is wholly incapacitated from further action or usefulness. If the K-kill occurs before the target's mission is completed, the mission is also aborted. A B-kill is associated with the case where an aircraft, ship, submarine, etc. fails to return to its base as a result of damage. An M-kill, or mobility kill, is associated with the loss of mobility, i.e., the target cannot move. There are other types of kills associated with complete or partial mission abortion or denial of war resources, which are used by analysts in assessing weapon/raid effectiveness and in wargaming. Therefore, it can be seen that this is another area that can be investigated in considerable detail to fully understand all of the intricacies associated with damage assessment and kill probability.

Sometimes the single shot kill probability of a missile will be given. Knowing this, it is possible to calculate the cumulative kill probability resulting from firing a number of missiles in a salvo or by ripple firing (sequentially firing a number of missiles at the same target). Figure 36 contains a plot of the cumulative kill probability versus the number of missiles fired as a function of the single shot kill probability. For example, given a missile with a single shot kill probability of 0.5, by firing two missiles the cumulative kill probability becomes 0.91, and by firing three missiles, the cumulative kill probability becomes 0.97. The graph shows the value of having a high single shot kill probability.

This results in a cost versus effectiveness trade-off that must be made by the missile fire control officer. Other factors may also enter into the decision regarding the number of missiles fired. For example, if there is sufficient time, and other considerations allow it, the shoot-look-shoot strategy may be used, where a second missile is not fired until it is determined that the first missile did not kill the target. This would minimize cost and conserve ordnance for engaging other targets.

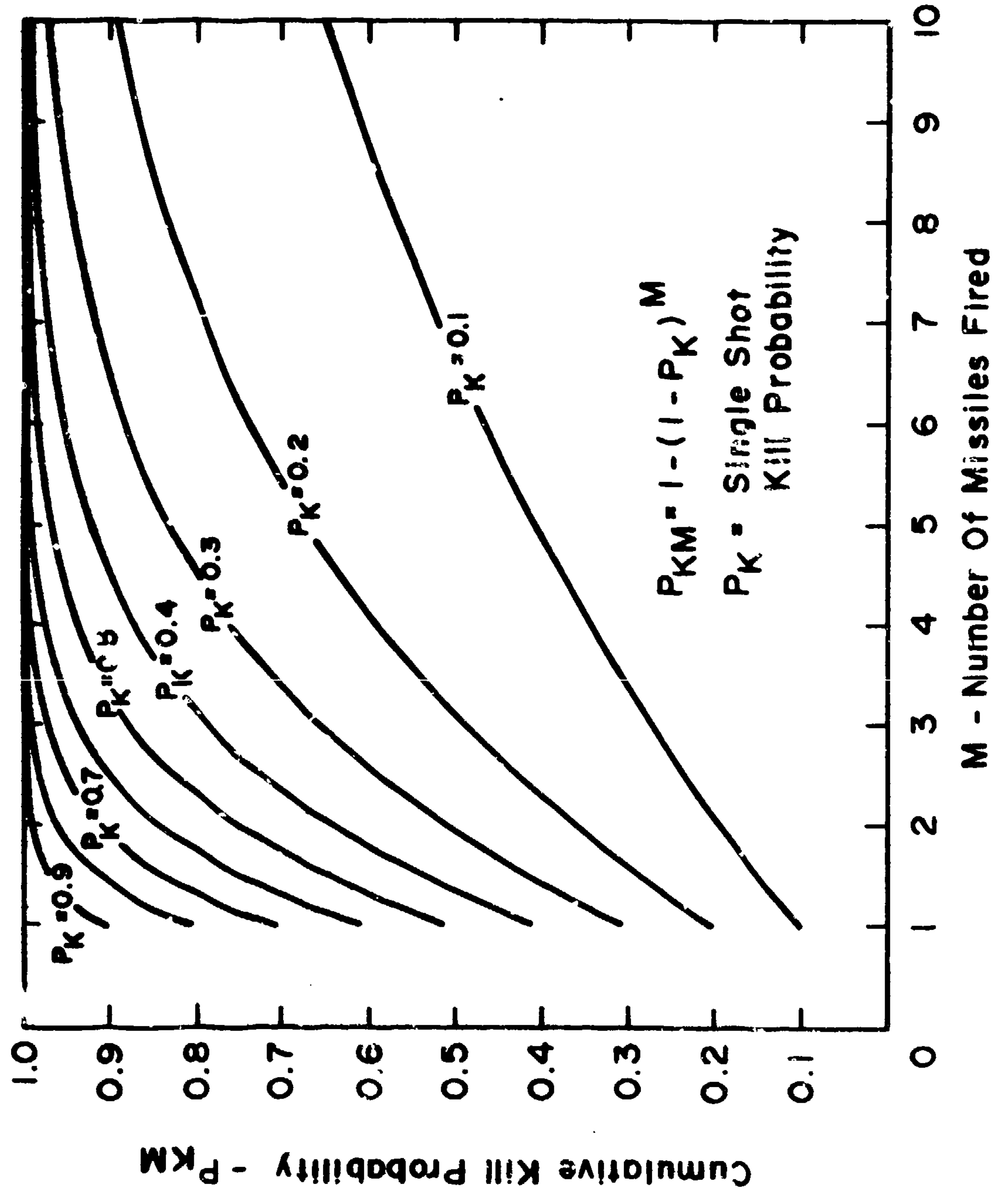


Fig. 36 CUMULATIVE KILL PROBABILITY

5. WHAT ARE THE TRENDS IN SMART WEAPONS?

Every block in Figure 1 has been discussed so far but one. That is the block on Technologies. The items listed are technologies or component applications where significant growth or improved capability may be expected over the next several years. Each of these items will be discussed briefly in this section. Before doing that, it may be best to put these technologies in the proper perspective.

5.1 Current Status

5.1.1 Precision

The continuing advancement of micro-electronic technology from integrated circuits (IC's) to medium-scale integrated (MSI) circuits to large-scale integrated (LSI) circuits has lead to a steady improvement in signal processing capability and reliability. This has resulted in improved precision, and consequent reduction in CEP's, of PGMs. The future introduction of very large-scale, very high speed, and ultra high speed, integrated circuits (VLSV, VHSIC, and UHSIC) approaching submicron feature size will mean more processing capability, lower cost, lighter weight, and increased versatility which will bring about greater signal processing capability in smaller PGM packages.

5.1.2 Guidance

The development of high frequency electromagnetic sources and detectors in small practical packages have provided improvements in range and angle resolution so that warheads could be guided to the target with a higher probability of kill. Laboratory efforts underway have already demonstrated two to five orders of magnitude increase in the sensitivity or output of detectors and active sources. Charge coupled devices (CCD), focal plane arrays (scanning and staring), integrated optics, fiber optics, and spectral filters have already appeared in breadboard and flight test hardware. The use of Kalman filters in small missiles and the development of multimode radomes and infrared domes offer unique performance capabilities. There has been a revolution in the adoption of digital technology for netting onboard PGM components and for computational purposes which will permit the implementation of complex guidance algorithms in future smart weapons.

5.1.3 Munitions

The advent of PGMs required the development of small, highly efficient warheads. Further advancements may be expected with new warhead liner designs, focused blast fragments, self-forging fragments, controlled detonation wave interactions, improved kinetic energy penetrations, new techniques for driving large fragments (approximately 1000 grains) at near shock velocities, and guidance-aided fuzing.

5.2 Generations

Progress in PGMs still closely parallels developments in munitions, sensors, and electronics. The most dominant effect of these three has been that of advancements in electronics. In fact, we may even rank various generations of PGMs by the status of electronic devices. These generations will track somewhat with the guidance improvements and availability of the conceptual, developmental, and fielded PGMs described later in this handbook.

5.2.1 Zeroth Generation

During the late 1940's and throughout the 1950's PGMs were developed based primarily upon electronic tube technology. Systems such as the air-to-air SIDEWINDER, surface-to-air BOMARC, NIKE AJAX, NIKE HERCULES, TARTAR, TERRIER, and TALOS, and the surface-to-surface PERSHING belonged to that era. These were not called PGMs, but were simply referred to as guided missiles.

5.2.2 First Generation

In the 1960's transistor technology was introduced to improve some of the older systems and to build new laser-guided bombs and wire-guided antitank missiles. The invention and application of the laser in the late 1950's provided a new energy source that gave a major impetus to the development of PGMs. The development of small television imaging tubes was also applied to new seekers. Systems like the GBU-15, WALLEYE, TOW, and DRAGON are in the field today using this technology.

5.2.3 Second Generation

The availability of integrated circuits and MSIs in the 1970's provided another opportunity for further improved performance in PGMs. Significant increases in the output and detection sensitivities of sources and sensors provided additional motivation. Systems recently introduced or soon to be

fielded such as the STINGER, COPPERHEAD, HELLFIRE, HARPOON, an MAVERICK were built on this technology. As in the past, when new technology comes along, many systems already fielded are upgraded with the new capability.

5.2.4 Third Generation

Major improvements in processors and microprocessors in the 1970's and the introduction of LSI's offer another order of magnitude promise for the 1980's. New MMW sources, imaging devices, lower power requirements, and new complex signal processing techniques add significant features to PGM's. These advancements are coming so fast that developmental systems are only partially fielded before major improvements are inserted. The second generation STINGER is already being adapted into the STINGER-POST, with production of the latter phased into making up a part of the total STINGER requirement.

5.2.5 Future Generations

Technology is moving ahead so quickly that fourth (VLSI and VHSIC) and fifth (UHSIC) generation components are already being tested in the laboratory. Imaging sensors have also moved ahead where 3-5 micron-scanning focal plane arrays (4th generation) and 8-12 micron staring focal plane arrays (5th generation) are only 2-3 years apart in predicted dates for systems applications. Some unique capabilities such as gyro-on-a-chip (6th generation technology) are on the horizon. The availability of this new technology and the awareness of its availability by decision makers at all levels presents some unusual management problems. People want to skip generations; they do not want to wait. Consequently, there is a tendency to slow down the work with the more immediate payoff and accelerate the more promising efforts. As a result, the development of weapons systems is stretched out by concentrating on technology during engineering development that should have been proven in advanced technology demonstrations. This delays introduction of new guided weapons into the inventory because something better is always on the horizon.

5.3 User Requirements

The users of PGMs are the shipborne, air defense, infantry, field artillery, mechanized infantry, attack helicopter, fighter and bomber troops in the field. Although PGMs require unique doctrine and tactics because of the extremely low CEPs and force multiplier effect, PGMs are still being deployed like conventional weapons. In fact, most people still think of PGMs

as just another dumb, albeit a little smarter, munition. Because of degradation due to weather, high cost which prevents adequate training, and occasional instances of reduced reliability, PGMs are not necessarily considered the wonder weapons they were touted to be. On the other hand, the user has had enough experience with PGMs and sufficient exposure to the new technology coming along that he has a long wish list on characteristics that should be in PGMs. Some of the general characteristics desired in PGMs are: simplicity, modularity, multipurpose, multimode, commonality, interoperability, night and adverse weather operation, and higher reliability, availability, maintainability, and dependability (RAM-D). The user would like all of these characteristics and "-ilities" at lower cost. Because of rapid obsolescence due to advancing technology, it is also desirable to have a built-in feature of easy product improvement or technology insertion.

There is also a list of specifics that different PGM launch platforms should have. Tactical aircraft need a capability of multiple kills per pass against ground targets. There is also a need for longer range engagement. Tanks need at least an 80 percent hit probability by the first round at up to 3 km. All launchers need to service at least twice the number of targets they do now. Automatic target cueing is high on everyone's list. A reliable technique is needed to defeat emitting targets such as radars when they shut down. Multitarget environments, where there are a variety of different targets, present the very real problem of making sure that the priority or high value targets are defeated first. Adding to this problem in the future is the use of decoys and countermeasures. The Soviets have the capability of bringing a whole suite of radioelectronic combat techniques to bear on Allied equipment. Broadband, and/or spot, noise jammers can be deployed against PGM sensors. Chaff, decoys, self-screening jammers, standoff jammers, and escort screening jammers are all possible threats. Intensive use of smoke is also an expected major countermeasure. The complement of forces and CM techniques known to be possessed by potential enemies demonstrates that something special will be needed in future conflicts. That something special will have to be provided by superior technology--fielded technology.

5.4 Technological Opportunities

As already indicated, the technologies block in Figure 1 is a prediction of those functions, devices, or technologies where major growth may be

expected that has a payoff in the future development of PGMs. A general summary of the types of opportunities listed would have to classify all of them as either materials or electronics based. The tendency, too, is to make things smaller, lighter, less costly, more functional, more reliable, and more modular. Ultimately, the aim is to use technology to make things simpler. In addition to the technologies described in Figure 1 and in the following paragraphs, there are new techniques and materials that will also give new versatility to PGMs. With new midcourse guidance devices and optimal control laws, bank-to-turn, instead of skid-to-turn, maneuvers may become feasible in small PGMs. Fast closing speeds against aircraft, cruise missiles, and possible tactical ballistic missiles will eventually necessitate guidance-aided fuzing. All PGM applications will benefit from new, lightweight, structurally strong, composite materials. Increased microprocessor capacity will mean the application of sophisticated target engagement techniques, as represented by Kalman filtering and/or optimal control laws in small PGMs. Major improvements in PGM capabilities will be made because of these and the following technological advancements.

5.4.1 Detectors/Sources

The most critical part of any PGM is usually its sensor. It is the sensor which picks up the target signature that is either emitted by the target naturally or is due to reflection of some external source of radiation. The part of the sensor which receives the target signal is the detector. If the PGM is an active system, the origin of the signal which is reflected off the target is the "source." Semiactive or bistatic systems separate the location of the source and detector. Although detectors and sources may have broad bandwidths, they tend to be confined to specific regions of the electromagnetic spectrum. Microwave/RF frequencies are generated by tubes and solid state power sources. The major demands for PGM applications are small lightweight, high-efficiency power sources. Increases in power output of two to three orders of magnitude are needed and may be achieved during the next decade. The effectiveness of microwave sources and detectors also rests upon improved designs in antenna configurations. Conformal arrays, interferometers, miniature phased arrays, and other concepts will see extensive trial-and-error testing. Similar requirements exist for millimeter wave sources and detectors. Solid IMPATT diode sources have not produced the expected power

levels. Tube applications in PGMs may yet prove successful. Laser sources such as ruby, gallium arsenide (GaAs), neodymium yttrium garnet (NdYAG), and carbon dioxide (CO_2) have been very successful. These will be improved further through higher efficiencies, elaborate coding, and smaller size. New rare earth lasers and gaseous lasers will expand the use of laser sources. Infrared devices depend upon a broad range of materials: lead sulfide (PbS), silicon (Si), selenium sulfide (SeS), mercury cadmium teluride (HgCdTe), indium antimonide (InSb), and indium arsenic antimonide (InAsSb). The major improvement goals for these materials is an order of magnitude increase in sensitivity and reduced cooling requirements. New IR and ultraviolet sensitive materials are less of a promise for the future than coupling of IR sensitive materials to microelectronic substrates for image processing.

5.4.2 VHSIC

Very high speed integrated circuits (VHSIC) are highly compact, complex electronic microcircuits that are capable of handling millions of instructions per second. VHSIC is another step in the progressive integration of electronic circuits or functions on a chip. The following table gives an approximate indication of the growth from discrete transistors to small-scale integrated (SSI) circuits to VHSIC and beyond.

Commercially Introduced	Component	Number of Circuits
1960	Transistor	1
1962	SSI	10
1966	MSI	10^2
1972	LSI	10^3
1982	VLSI/VHSIC	10^4
1986	ULSI/UHSIC	10^5

As integration increases to higher and higher complexity of circuits, there may have to be trade-offs between speed and versatility. For that reason, two different nomenclatures are used although the distinction is not meaningful except for specific chip functions.

In addition to the number of circuits on a chip, various microcircuits are often rated in terms of linewidths or features sizes. Medium-scale integrated (MSI) circuits, which were introduced during 1966-72, have 10 micron line widths. Large-scale integrated (LSI) circuits which are presently being

used in some PGMs have 5 micron features. In 3-5 years, very large-scale integrated (VLSI) circuits with 2 micron linewidths will be seen in systems. Within 4-10 years, VHSIC (with linewidths of 1.3 microns) is expected with a further goal of submicron scale (approximately 0.5 micron) circuits referred to as ultra-high speed integrated circuits (UHSIC). The limit may be reached at 0.1 to 0.5 micron. The purpose of this incessant push for microminiaturization is to make devices using less electric power (factor of 10 decrease), to increase clock rates from 10 MHz for LSI to 250 MHz for VHSIC, to put more gates or devices on a chip (up from 3×10^3 to 1.5×10^5 gates), to push processing speed from 1 to 10^4 million instructions per second (MIPS), and to reduce chip size by 10 to 20 times for the same operation. There are a number of military applications needing these advancements in technology: weapon targeting, radar, image processing, wideband data communications, and electronic warfare. PGMs will be one of the major users.

5.4.3 CCD

A charge coupled device (CCD) is a means of moving extremely small aggregated units of electrical charge from one fixed position to another. The process is analogous to a bucket brigade where buckets of electrons are moved from place to place along a chain. One type of CCD has actually been referred to as a bucket brigade because charges were moved serially in this manner. Another variation of a CCD is a charge injection device (CID). All CCDs are based upon metal oxide semiconductor (MOS) technology. The primary advantage of CCDs is highly controlled transfer of small units of charges. This property makes CCDs useful in serial memories, buffers, computers, digital signal processors, and imaging devices. Trade-offs in the use of CCDs depends upon memory volatility, speed of access, packing density, and cost. CCDs will find major applications in PGMs.

5.4.4 Microprocessors

A microprocessor is a computer, or at least its primary logic and arithmetic operations, on a square chip of silicon about 5 millimeters on a side. The combination of a microprocessor with other chips which serve as input/output devices, program memories, random-access memories, timing circuits, and various interfaces, make up a microcomputer. Microprocessors came into being with the advent of large-scale integrated circuits in the early 1970s. There has almost been a new generation of microprocessors every two

years since 1971. This growth has not been due so much to the advancement of the central processor unit itself, but due to the fact that solid state memories have increased in speed by 30 percent per year for ten years. This trend is continuing. The use of CCD and bubble memory peripherals will increase the capacity of microprocessors in the future. PGMs can make use of embedded microprocessors to sense, modulate, and control input and output of the various components, such as propulsion, actuators, target sensor, altitude sensor, fuze, and gyroscopes. The individual distributed microprocessors may be netted or federated into a central master microprocessor and microcomputer to form the overall control and communication system within the missile. Extremely high memory capacities measured in megabits per chip, and computation speeds approaching 1000 million instructions per second will make autonomous image recognition and multimode/band operation a reality.

5.4.5 Fiber Optics

Fiber optics are flexible glass filaments over which signals (pulses of light) may be transmitted. They possess advantages of small size, lightweight, wide bandwidth (which permits more channels per cable), limited cross-talk between channels, and very good resistance to electromagnetic interference. Major improvements are expected in the future in terms of reducing signal loss. Transmission of signals over long distances has not been possible using this technology until recent years because of the decay and scrambling of the signal with transmission distance. Losses have dropped from 20 decibels per kilometer to 10 db/km to 2-5 db/km. Improvements are bringing these losses down to below 1 db/km. Signal loss is a function of the wavelength of the light used as the signal. Generally, losses decrease as the wavelength increases. Losses are also a function of the fiber diameter, index of refraction of the glass, purity, and dopants. Fiber optics find use in communications (commercial telephone systems) and data links, and may be thought of as a replacement for metallic wires and coaxial cables. Because of the wide bandwidth, it is possible to transmit high resolution images (as in television) through fiber optics. Based upon the small size and weight of the fiber, it may become possible to transmit TV images from a remotely piloted vehicle to a ground station 10-15 km away. The same concept may be applied to guidance of a PGM, where the operator would receive pictures of the target area from the sensor and send guidance signals to the missile over the same

fiber. Fiber optics will probably find many uses as data links within PGMs and in their airborne and ground launcher support equipment.

5.4.6 Surface Acoustic Wave (SAW) Devices

Certain materials have the property of propagating sound waves at microwave frequencies across their surfaces just like waves on the surface of water. Devices may be made out of these materials which are very small, have long life, are highly reliable, and possess unusual and sometimes frequency dependent bandwidths. Long-range trends will improve their temperature stability, reduce insertion losses, expand frequency application, and develop new materials that will expand capability. SAW devices are basic components in delay lines, frequency filters, phase shifters, discriminators, oscillators, convolvers, amplifiers, memories, and programming circuits. Many applications of SAW devices are possible relative to PGMs and their launch platform or target acquisition system.

5.4.7 Integrated Optical Circuits

Integrated optics is the technology of optical circuit miniaturization. The goal of present research in integrated optics is to incorporate, on a single small substrate, all of the optical components needed in a given optical circuit. This would include, for example, sources, modulators, detectors, filters, waveguides, lenses, prisms, and mirrors. Waveguides and other passive devices to manipulate a beam of light are formed in the integrated optical circuits (IOCs) by properly varying the index of refraction throughout the circuit material. SAW devices are frequently used as a component in IOCs. IOCs offer the user small size, low power consumption, high efficiency, and stability. The long-range trend is the same as with most of the growth technologies. IOCs will become smaller, more efficient, more adaptable, and be developed with interfaces so as to be a modular option in electronic circuit design. Use in PGMs for signal processing and image generation should significantly reduce their cost and improve their performance.

5.4.8 Focal Plane Array Sensors

A focal plane array (FPA) is a collection of individual sensors which detect passive radiation primarily in two bands, 3-5 microns and 8-12 microns. The main objective of using an FPA is for the purpose of imaging. Current efforts are aimed at coupling the FPA output to a microprocessor with a

sophisticated pattern recognition algorithm to automatically recognize and identify targets. There are two basic methods of imaging with detector arrays. One is to mechanically scan the scene to generate image data from a relatively small number of detectors. The other is to optically focus the scene on a two-dimensional array and sample each element electronically to produce scene data and images. Systems that image the total field of view on the focal plane array operate in a staring mode. In this case, the instantaneous field of view is the same as the total field of view and there is no motion of the image with respect to the focal plane array. Systems that image only a portion of the total field of view (the instantaneous field of view) on the focal plane array and move this instantaneous field of view about to cover the total field of view operate in a scanning mode. Detectors in these arrays may be discretely hard wired, monolithic with the CCD signal output channels, or some hybrid combination of these. Individual detectors of an FPA form the smallest picture element, called pixels, which determines the resolution possible. Progress is most advanced for staring mode arrays operating at 3-5 microns, but the long-range trend is toward scanning arrays that operate at 8-12 microns, for FLIR compatibility. Variables in FPAs include staring vs. scanning, detector size, number of detectors, materials, uniformity of response, field of view, resolution, coding requirements, temperature of operation, array density, shelf life, and size requirements. The major goal of exploring all of these variables is to eventually obtain a compact, self-contained, low-cost, night/adverse weather, high-resolution imaging system. A very large number of applications are possible in target detection, fire control, and PGM systems. Automatic target cuers, thermal weapon sights, standoff imaging surveillance, fire and forget seekers, automatic target hand-off to missiles, mast-mounted sights, adaptive gate/correlation/moving target trackers, and autonomous acquisition seekers are among the specific applications.

5.4.9 Microgyros

Another step in the direction of miniaturization is to essentially put a gyroscope on a chip. Reduced size is the major advantage along with reduced cost. The approach being taken may also eliminate some of the problems associated with ring laser gyros: lock-in at low rotation rates, bias drift, and other variables due to the gain medium in the ring cavity. Microgyros

still use the fundamental approach employed in ring laser gyros. The theory of relativity states that no signal may be propagated faster than the speed of light. Consequently, laser or light beams moving with or against the direction of acceleration of a platform, such as a PGM, exhibit interference patterns and frequency variations when compared to each other. Accumulated measurements based on these comparisons give a measure of the rotation experienced by the sensor. The trend is to use single or multiple fiber optic rings or integrated optical circuits as building blocks for these microgyros. A possible limitation to the use of this device is the current rule of thumb that the accuracy of a ring laser gyro decreases with decreasing optical path length, however, there may be ways of maintaining reasonable path lengths in a small size package.

5.4.10 Radomes/IR Domes

Seekers and sensors on PGMs need a window through which the target signal is received and/or the active signal is transmitted. This is usually called a radome or IR dome.

Electrical and aerodynamic considerations present conflicting requirements in dome design for high speed radar guided missiles. Because of refraction when a signal passes through different materials, a hemispherical radome provides the best electrical performance, but aerodynamically it is one of the worst shapes in terms of drag. Through compromise, most missile radomes have a long tapered shape known as an ogive. This provides fairly low drag but leaves a lot to be desired in terms of electrical performance. Infrared/optical seekers employ a segment of a sphere as a dome shape. Because the aperature of such systems is fairly small, this segment makes up only a small portion of the nose area and the remainder of the missile's nose is tapered to minimize drag.

Most domes in use today or under development are intended for narrowband systems. With the trend towards broadband, multiband, and multimode operation, new demands are being placed upon radome and IR dome materials and design. Increased flight speeds also demand extensive efforts to reduce the aerodynamic drag on PGMs, decrease rain erosion, and cut down on vulnerability to possible laser weapons. Another problem, that of boresight error, is introduced by the dome shape, material employed, and possible operations. As the signal goes through the dome, its path angle may be distorted due to

refraction. Consequently, the PGM does not follow a true line of sight to the target and unless precautions are taken in the design guidance instability can result. Aerodynamic heating and erosion contribute to the problem. Over the next few years, extensive effort will go into the development of new materials for the reduction of radome boresight errors and expansion of their transmission characteristics in the microwave region from 2 to 18 GHz. Domes that embrace the microwave and millimeter region from 10 to 35 GHz band will also receive attention. New materials like ternary sulfide already exhibit dual windows from 8-18 microns in wavelength and 17-18 GHz (18 mm), with both a greater hardness and higher melting point than current materials. The advantages of a single broadband dome are reduced design complexity, ease of packaging multimode components, and reduced drag. As usual, trade-offs will have to be made in optimizing refraction versus drag characteristics. In lieu of an actual change in dome materials and construction, progress will be made in adaptive compensation through use of algorithms that correct the guidance input based upon predicted changes in the boresight error over the flight path.

5.4.11 Digital Technology

Many guidance and control sensors generate signals that are continuous outputs that are a function of time. These outputs are analog signals which require their own dedicated channel for transmission to another point in the guidance and control system. If the signal is converted to a discrete or digital output, however, it can be multiplexed with many other digital signals over a single channel or bus. Several factors have come together to make digital transmission the preferred approach. During 1976-77, Military Standard 1553-B was revised, and a standard multiplexing protocol was adopted. Analog-to-digital convertors also became more readily available and cheaper. Single twisted pairs of wires for multiplexed digital signals were recognized as being less vulnerable and more reliable in military systems. The availability of microprocessors that could be netted, distributed, or federated with a standard bus opened up a whole new range of possibilities. Modular components could also be used as plug-in, take-out units on a standard bus. Consequently, there has been an increase in the application of multiplexing techniques to avionics, fire control, and PGM systems. The use of digital signal transmission will continue to expand in future weapon systems.

6. CONCLUSION

All of the blocks in Figure 1 have now been discussed. It should be obvious by now that a PGM is a very complex package that has been subjected to numerous trade-off decisions in its design. Advances in technology will add to the list of options that must be considered in the future. It is because there are so many different options for different circumstances that there are so many different PGM's. The authors hope that this tutorial description, which is more technical than planned, will help in understanding why so many different approaches to PGMs are contained in Volume 2 of this handbook. A glossary is appended to this volume to aid in this understanding. Smart missiles require smart people.

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GLOSSARY

A

acceleration	The rate of change of velocity.
accelerometer	A sensor or transducer which measures acceleration.
acquisition	The process of detecting and recognizing a target and locking the tracking devices on to the target signal.
active	A device or system that generates or radiates energy.
active guidance	A homing guidance system that transmits a signal which is reflected by the target for guidance purposes.
active homing	The homing of a missile in which energy waves (as radar) are transmitted from the vehicles to the target and reflected back to the vehicle to direct the vehicle toward the target. Compare passive homing.
aerodynamic force	The force exerted by a moving gaseous fluid upon a body completely immersed in it.
air breather	An aerodynamic vehicle propelled by fuel oxidized by intake from the atmosphere; an air breathing vehicle.
air frame	The assembled structural and aerodynamic components of an aircraft or missile that support the different systems and subsystems integral to the vehicle.
air launch	To launch from an aircraft in the air, as to air launch a guided missile.
algorithm	A special mathematical procedure for solving a particular type of problem.
altimeter	Device for measuring altitude above the ground.
analog to digital conversion	A process by which a sample of analog information is transformed into a digital code.
angle gate	An electronic circuit that only passes signals received from objects located within set angular limits about some reference direction. Used to discriminate against unwanted signals, usually in radars or antiradiation seekers

angle of attack	The angle between the longitudinal axis of an air frame and its velocity vector.
angle of incidence	The angle at which a ray of energy impinges upon a surface, usually measured between the direction of propagation of the energy and a perpendicular to the surface at the point of impingement.
angstrom	A unit of length equal to 10^{-10} meters.
angular acceleration	The rate of change of angular velocity.
angular rate	Change of direction per unit of time.
angular resolution	The fineness with which two targets can be resolved in angle.
antenna	A system of conductors for radiating or receiving radio waves.
antenna pattern	= radiation pattern.
antiradiation missile (ARM)	A homing missile intended to destroy radars by homing on their radiation.
aperture	An opening; used to define the size or effective diameter of an antenna or lens system.
ARM	= antiradiation missile.
atmospheric refraction	Refraction resulting when a ray of radiant energy passes obliquely through the atmosphere.
attenuation	Reduction in intensity.
automatic control	Control of devices and equipment by automatic means.
automatic pilot	Equipment which automatically stabilizes the attitude of a vehicle about its pitch, yaw, and roll axes. Also called autopilot.
automatic tracking	Tracking in which a control system automatically follows some characteristic of a signal; specifically, a process by which a tracking system is enabled to keep its antenna continually directed at a moving target without manual operation.
autopilot	= automatic pilot.
azimuth	Horizontal direction or bearing.

B

background	Any effect in a sensor or other apparatus or system above which the phenomenon of interest must manifest itself before it can be observed.
back scatter	= backward scatter. The scattering of radiant energy into the hemisphere of space bounded by a plane normal to the direction of the incident radiation and lying on the same side as the incident ray; the opposite of forward scatter. Also called back scattering.
ballistic missile	A missile designed to operate primarily in accordance with the laws of ballistics.
ballistics	The science that deals with the motion, behavior, and effects of projectiles, especially bullets, bombs, rockets, or the like.
ballistic trajectory	The trajectory followed by a body being acted upon only by gravitational forces and the resistance of the medium through which it passes.
bang-bang control	Control of a guided missile by movement of the control surfaces back and forth between their extreme positions. Compare to proportional control.
beam	A ray or collection of focused rays of radiated energy.
beam rider	A guidance technique where the vehicle automatically follows a radar, radio, laser, light, or other type of beam along the desired path.
beamwidth	A measure of the concentration of power of a directional antenna. It is the angle subtended at the antenna by arbitrary power-level points across the axis of the beam. This power level is usually the point where the power density is one-half that which is present at the axis of the beam at the same distance from the antenna (half power points or 3 db points).
bearing	The horizontal direction of an object or point, usually measured clockwise from a reference line or direction through 360°.
bias error	A measurement error that remains constant in magnitude for all observations. A kind of systematic error.

boattail — The rear portion of a missile or rocket having decreasing cross-sectional area toward the rear.

boresight error — The angular error between the mechanical and electrical axis of an antenna or lens system. Sometimes used to define the linear displacement between two parallel lines of sight.

burnthrouh — Term used to denote when a radar detects the target echo while being subjected to noise jamming. Burnthrough can be accomplished by increasing the radar's transmitted power and/or by decreasing the range between the radar and the target. Burnthrough range is the slant range at which burnthrough occurs.

C

canard — Control surface placed forward of the main lifting surface in an aerodynamic vehicle.

carrier — = carrier wave.

carrier frequency — The frequency of a carrier wave; the frequency of the transmitted signal.

carrier wave — A wave generated at a point in the transmitting system which is modulated by the information signal; the primary signal generated in a transmitter.

Cartesian coordinates — A coordinate system in which the location of points in space are expressed by reference to three planes which intersect at right angles.

celestial guidance — The process of directing movements of a vehicle, especially in the selection of a flight path, by reference to celestial bodies.

chaff — Reflectors introduced into the atmosphere to produce radar echos; used to confuse radar systems by generating false targets or masking real targets. A form of countermeasures. Sometimes called window (British).

chirp — An all-encompassing term for various techniques of pulse expansion-pulse compression applied to pulse radar; employed to improve the range resolution of radar systems or to improve the signal to noise ratio without degradation to range resolution.

circular error probable (CEP) — A measure of the accuracy with which a missile can be guided; the radius of the circle at a specific distance in which 50 percent of the reliable shots land. Also called circle of equal probability, circle of probable error.

closed-loop system — A system in which the output is used to partially control the input. See feedback control loop.

clutter — Extraneous signals which tend to obscure the reception of the desired signal in a radar or electro-optical system. Examples are ground clutter, atmospheric clutter, or sea clutter.

coasting flight — The flight of a missile after the rocket motor burns out.

code — A system of symbols, pulses, or signals for representing information and the rules for associating them.

coherence — In radar, a relation between wave trains such that, when they are brought into coincidence, they are capable of producing interference phenomena.

coherent — In electromagnetic radiation, being in phase, so that waves at various points in space act in unison, as in a laser producing coherent light. Having a fixed relation between frequency and phase of various signals.

coherent radar — A type of radar that employs circuitry which permits comparison of the phase of sucessive received target signals.

command guidance — The guidance of a missile by means of electronic signals sent to receiving devices in the vehicle.

conical scanning — Scanning of an antenna beam where the direction of maximum radiation generates a cone whose vertex angle is of the order of the beamwidth. Used in tracking radar.

continuous wave radar — A general species of radar transmitting continuous waves, either modulated or unmodulated. The simplest form transmits a single frequency and detects only moving targets by the Doppler effect. This type of radar determines direction and velocity of the target. Also called CW radar. Compare pulse radar.

continuous waves — Waves, the successive oscillations of which are identical under steady-state conditions.

control — To direct the movements of a missile with particular references to changes in attitude and speed. Compare guidance.

correlation — In statistics, a relationship between two occurrences which is expressed as a number between minus one (-1) and plus one (+1).

countermeasures — Intentional interference with the operation of a system. See interference, electronic countermeasures.

cross section — See radar cross section.

D

damping — The suppression of oscillations or disturbances.

data link — Any communications channel or circuit used to transmit data.

decibel (dB) — A dimensionless measure of the ratio of two power levels, equal to 10 times the logarithm to the base 10 of the ratio of the two powers P_1/P_2. 3 dB is approximately a factor of two (2) and 10 dB is a factor of 10. By adding 3 dB, a ratio is doubled; by subtracting 3 dB, a ratio is halved. By adding 10 dB a ratio is increased by a factor of 10; by subtracting 10 dB, a ratio is reduced by a factor of 10.

demodulator — An electronic device which operates on an input of a modulated carrier to recover the modulating wave as an output.

detection — The process of interpreting stimuli to the extent of concluding that an object (target) is present at some distance from the observer. See recognition.

detector — (1) = sensor. (2) An instrument employing a sensor to detect the presence of something in the surrounding environment.

diffraction — The process by which the direction of radiation is changed so that it spreads into the geometric shadow region of an opaque or refractive object that lies in a radiation field.

diffuse reflection	Any reflection process in which the reflected radiation is sent out in many directions usually bearing no simple relationship to the angle of incidence; the opposite of specular reflection.
digital	Using discrete expressions to represent variables.
directional antenna	An antenna that radiates or receives signals more efficiently in some direction(s) than in others.
directivity	The ability of an antenna to radiate or receive more energy in some direction(s) than in others. See beam.
Doppler effect	The change in frequency with which energy reaches a receiver when the receiver and/or the energy source are in motion relative to each other. Also called Doppler shift.
Doppler radar	A radar which detects and interprets the Doppler effect in terms of the radial velocity of a target.
drag	A retarding force acting upon a body in motion through a fluid, parallel to the direction of motion of the body.
drone	A remotely controlled aircraft.
ducting	The trapping of an electromagnetic wave between two layers of the atmosphere, or between a layer of the atmosphere and the earth's surface. Results in longer distance propagation than normal.

E

echo	A wave that has been reflected or otherwise returned with sufficient magnitude and delay to be detected as a wave distinct from that directly transmitted. In radar, a pulse of radio frequency energy reflected from the target.
effective aperture	In antenna design, the aperture of an antenna that determines its gain. This is always less than the physical aperture.
effective area	In antenna design, the area of an antenna that determines its gain. The equation in general use for effective area is: $A = \lambda^2 G/4\pi$, where G is the gain at a given wavelength, λ.

electromagnetic radiation	Energy propagated through space or through material media in the form of an advancing disturbance in electric and magnetic fields existing in space or in the media. The term radiation, alone, is commonly used for this type of energy.
electronic countermeasures (ECM)	Intentional interference generated to disrupt the operation of radio or radar systems. Also called jamming.
electronic warfare (EW)	Military action involving the use of electromagnetic energy to determine, exploit, reduce, or prevent an enemy's use of the electromagnetic spectrum and action which retains friendly use of the electromagnetic spectrum.
electromagnetic wave	A wave produced by oscillation of an electric charge.
electro-optical	Generally refers to devices that employ both optical (IR, visible, UV) sensors or processors and electronics.
emission	With respect to electromagnetic radiation, the process by which a body emits electromagnetic radiation as a consequence of its temperature only.
envelope	See launch envelope.
error signal	A voltage the magnitude of which is proportional to the difference between an actual and a desired position.
extinction	The attenuation of light; that is, the reduction in illuminance of a collimated beam of light as the light passes through a medium wherein absorption and scattering occur.

F

feedback	The return of a portion of the output of a device to the input; positive feedback adds to the input, negative feedback subtracts from the input.
feedback control loop	A closed transmission path (loop), which includes an active tranducer and which consists of a forward path, a feedback path, and one or more mixing points arranged to maintain a prescribed relationship between the loop input signal and the loop output signal.

fermi — A unit of length equal to 10^{-13} centimeters.

fire and forget — Term applied to weapon system that does not require operator assistance to guide missile once it is fired.

flare — A source of IR radiation ejected from a target that is intended to act as a decoy to an attacking IR guided missile. Usually a combustible solid or liquid that burns to produce an extremely hot flame.

FLIR — Forward looking infrared; and imaging system that uses IR energy used for target acquisition at night or when visibility is poor.

focal plane array — An array of small solid state sensors placed in the focal plane of an imaging system to convert the energy received into an electrical output. Generally operate in the IR and visible spectrum.

forward scatter — The scattering of radiant energy into the hemisphere of space bounded by a plane normal to the direction of the incident radiation and lying on the side toward which the incident radiation is advancing; the opposite of backward scatter.

F-pole — The distance between the launch aircraft and target at the time the missile reaches the target.

frequency — Of a function periodic in time, the reciprocal of the primary period. The unit is the cycle per unit time. Usually specified in hertz (Hz) meaning cycle per second.

frequency band — A continuous range of frequencies extending between two limiting frequencies.

fuze — A device that controls the detonation of the warhead.

G

g or G — An acceleration equal to the acceleration of gravity, 980.665 cm/sec^2, approximately 32.2 ft/sec^2 at sea level.

gain — A increase or amplification. In radar there are two general usages of the term: (a) antenna gain is the ratio of the power transmitted along the beam axis to that of an isotropic radiator transmitting the same total power; (b) receiver gain is the amplification given a signal by the receiver.

gate — To control passage of a signal in electronic circuits. A circuit having an output and inputs so designed that the output is energized only when a definite set of input conditions are met. See range gate, velocity gate, angle gate, tracking gate.

gating — The process of selecting those portions of a signal which exist during one or more selected time intervals, in selected frequency bands, or which have magnitudes between selected limits.

gimbal — A device with two mutually perpendicular and intersecting axes of rotation, thus giving free angular movement in two directions, on which an antenna, lens, mirror, or other object may be mounted.

ground clutter — Radar echoes reflected from the terrain. Also, emissions from the ground in the IR region that compete with the target emission. Sea clutter is similar but is produced by the sea.

guidance — The process of directing the movements of an aeronautical vehicle with particular reference to the selection of a flight path.

guidance law — An algorithm that determines the direction in which a missile is to fly in order to intercept the target based upon measurement of the relative motion between the missile and the target.

guided missile — Broadly, any missile that is subject to, or capable of, some degree of guidance or direction after having been launched, fired, or otherwise set in motion. Specifically, an unmanned, self-propelled flying vehicle (rocket) carrying a destructive load and capable of being directed or of directing itself after launching, responding either to external direction or to direction originating from devices within the missile itself.

gyro — A device which utilizes the angular momentum of a spinning mass (rotor) to sense angular motion of its base about one or two axes orthogonal to the spin axis. A gyroscope.

H

half-power points — The points on the radiation pattern of an antenna where the transmitted power is one-half that of the maximum of the same lobe.

hertz (Hz) — The unit of frequency, cycles per second.

home — To follow a path of energy waves, especially radio, radar, or light waves, by means of a directional antenna, radar equipment, or other sensing device, to or toward the point of transmission or reflection of the waves.

homing — The following of a path of energy waves to or toward their source or point of reflection. See home, homing guidance.

homing guidance — Guidance in which a missile is directed toward a destination by information received from the destination. See active guidance, semiactive guidance, passive guidance.

I

illuminance — The total luminous flux received on a unit area of a given real or imaginary surface, expressed in foot-candles, lux, or phot. Illuminance is analogous to irradiance, but is to be distinguished from the latter in that illuminance refers only to light.

illuminator — A radar transmitter used to illuminate a target so that the reflected energy can be used for semiactive guidance.

index of refraction — A measure of the amount of refraction. The ratio of the wavelength or phase velocity of an electromagnetic wave in a vacuum to that in the substance.

inertial guidance — Guidance by means of the measurement of acceleration from within the craft.

infrared (IR) — Pertaining to infrared radiation.

infrared dome — A cover, transparent to infrared energy, placed over the seeker of an infrared guided missile to protect it from the environment.

infrared radiation — Electromagnetic radiation lying in the wavelength interval from about 0.75 microns to an indefinite upper boundary arbitrarily set at 300 microns.

integrating accelerometer — A transducer designed to measure, and capable of measuring, velocity by means of a time integration of acceleration.

interface — A common boundary between two or more parts of a system.

interference — Extraneous signals, noises, etc. that hinder proper reception of the desired signal in electronic equipment.

interferometer — A device used to produce and measure interference between portions of a coherent wave train or two or more wave trains. In radar, an interferometer antenna is used to sense the direction from which a signal is received.

irradiance — = radiant flux density

isotropic antenna — A hypothetical antenna that radiates or receives energy uniformly in all directions. Has a gain of one in all directions.

isotropic radiator — An energy source that radiates uniformly in all directions.

J

jamming — Intentional transmission or reradiation of radio signals in such a way as to interfere with reception of desired signals by the intended receiver.

jet reaction — A jet that develops thrust by its reaction to a substance ejected from it; specifically a jet or stream of gas created by the burning of fuel.

jet vane — A vane, either fixed or movable, used in a jet stream for purposes of stability or control of a missile.

K

kilo (k) — Prefix meaning multiplied by 10^3.

kilohertz (KHz) — One thousand hertz or 1000 cycles per second.

kinematics — The branch of mechanics dealing with the description of the motion of bodies without reference to the forces producing the motion.

kinetic energy — The energy which a body possesses as a consequence of its motion, defined as one-half the product of its mass, m, and the square of its speed, v; $1/2\ mv^2$.

L

laminar flow — A smooth flow in which no crossflow of fluid particles occur between adjacent stream lines; hence, a flow conceived as made up of layers. Commonly distinguished from turbulent flow.

laser — (From light amplification by stimulated emission of radiation.) A device for producing light by emission of energy stored in a molecular or atomic system when stimulated by an input signal.

lateral — Of or pertaining to the side; directed or moving toward the side.

lateral acceleration — Acceleration substantially along the lateral axis of a missile, aircraft, etc.

launch — To send off a rocket vehicle under its own rocket power, as in the case of guided aircraft rockets or artillery rockets.

launch and leave — Term applied to an air launched missile system which does not require the launch aircraft to support the guidance of the missile after it is launched, allowing the aircraft to leave the area.

launch envelope — A theoretical inner and outer boundary around a target that sets the minimum and maximum range from which a missile can be launched in order to hit the target.

launching rail — A rail that gives initial support and guidance to a rocket launched in a non-vertical position.

lift — The component of the total aerodynamic force acting on a body perpendicular to the undisturbed airflow relative to the body.

light — Visible radiation (about 0.4 to 0.7 microns in wavelength) considered in terms of its luminous efficiency, i.e., evaluated in proportion to its ability to stimulate the sense of sight.

line of sight — The straight line between the eye of an observer and the observed object or point. Any straight line between one point and another, or extending out from a particular point. In radio, a direct propagation path that does not go below the radio horizon.

lobe	An element of a beam of focused radio energy. Lobes define surfaces of equal power density at varying distances and directions from the radiating antenna.
lock, to lock-on	Of a radar or other sensing and tracking device. To acquire a particular object of interest and continue tracking it automatically in range, angle, or velocity.
loss	A decrease in signal power in transmission from one point to another. Loss is usually expressed in decibels.

M

Mach number	A number expressing the ratio of the speed of a body or of a point on a body with respect to the surrounding air, or the speed of a flow, to the speed of sound in the medium; the speed represented by this number. If the Mach number is less than one (1), the flow is called subsonic and local disturbances can propagate ahead of the flow. If the Mach number is greater than one (1), the flow is called supersonic and disturbances cannot propagate ahead of the flow, with the result that shock waves form.
magnetic	(1) of or pertaining to a magnet, (2) of or pertaining to a material which is capable of being magnetized.
magnetometer	An instrument used in the study of geomagnetism for measuring the magnetic characteristics of the earth. Used to detect magnetic disturbances due to man-made objects such as submarines or ships.
main bang	The transmitted pulse, within a radar system.
map matching guidance	The guidance of an aircraft or missile by means of a radarscope film proviously obtained by a reconnaissance flight over the terrain of the route, and used to direct the vehicle by aligning itself with radar echoes received during flight from terrain below.
micron (μ)	A unit of length equal to one-thousandth of a millimeter.
microsecond	One-millionth of a second.

microwaves — Commonly, that region of the radio spectrum between approximately 1 GHz and 300 GHz (corresponding wavelengths are 30 centimeters to 1 millimeter).

midcourse guidance — Guidance of a missile from the end of the launching phase to some arbitrary point or at some arbitrary time when terminal guidance begins.

millimeter (mm) — One-thousandth of a meter.

missile — Any object thrown, dropped, fired, launched, or otherwise projected with the purpose of striking a target.

mode — A functioning position or arrangement that allows for the performance of a given task.

modulating wave — See modulation.

modulation — (1) The variation in the value of some parameter characterizing a periodic oscillation. (2) Specifically, variation of some characteristic of a radio wave, called the carrier wave, in accordance with instantaneous values of another wave, called the modulating wave. Variation of amplitude is amplitude modulation, variation of frequency is frequency modulation, variation of phase is phase modulation, variation of duration is pulse modulation.

moment — A tendency to cause rotation about a point or axis, as of a control surface about its hinge or of a missile about its center of gravity; the measure of this tendency, equal to the product of the force and the perpendicular distance between the point or axis of rotation and the line of action of the force.

multiplexing — The simultaneous transmission of two or more signals within a single channel.

N

natural frequency — (1) The frequency of free oscillations of a system. (2) The undamped resonant frequency of a physical system. The system may be mechanical, pneumatic, or electrical. As in the natural frequency cff a missile airframe.

navigation	The practice or art of directing the movement of a craft from one point to another. Navigation usually implies the presence of a human aboard the craft.
noise	Any unwanted disturbance within a frequency band, such as undesired electrical waves in a transmission channel or device. An erratic, intermittent, or statistically random oscillation.
normal distribution	The fundamental frequency distribution of statistical analysis. Also called Gaussian distribution.

O

ogive	A body of revolution formed by rotating a circular arc about an axis that intersects the arc; the shape of this body; the shape of a nose of a projectile or missile.
open loop	A system operating without feedback.
operational envelope	See launch envelope.
optimal	Pertaining to a trajectory, path, or control motion, one that minimizes or maximizes some quantity or combination of quantities such as fuel, time, energy, distance, etc. This optimum condition, or path, is commonly calculated by a type of mathematics known as calculus of variations.
orthogonal	Originally, at right angles; later generalized to mean the vanishing of a sum (or integral) of products.
oscillation	(1) Fluctuation or vibration on each side of a mean value or position. (2) The variation, usually with time, of the magnitude of a quantity with respect to a specified reference when the magnitude is alternately greater and smaller than the reference.
out of phase	The condition of two or more cyclic motions which are not at the same part of their cycles at the same instant.

P

parameter — In general, any quantity of a problem that is not an independent variable. More specifically, the term is often used to distinguish, from dependent variables, quantities which may be assigned more or less arbitrary values for purposes of the problem at hand.

passive homing — The homing of a missile wherein the vehicle directs itself toward the target by means of energy waves transmitted or radiated by the target. See active homing.

passive guidance — Guidance in which a missile is directed toward a destination by means of the natural radiations from the destination.

pencil beam — An antenna radiation pattern having high directivity so as to form a narrow beamwidth having a circular cross section in a direction perpendicular to the direction of maximum radiation.

period — The interval needed to complete a cycle. Specifically, the interval between passages at a fixed point of a given phase of a simple harmonic wave; the reciprocal of frequency.

periodic quantity — In mathematics, an oscillating quantity whose values recur for certain increments of the independent variable.

phase — Of a periodic quantity, for a particular value of the independent variable, the fractional part of a period through which the independent variable has advanced, measured from an arbitrary reference. In the case of a simple harmonic quantity, the reference is often taken as the last previous passage through zero from negative to positive direction.

photoelectric cell — A transducer which converts electromagnetic radiation in the infrared, visible, and ultraviolet regions into electrical quantities such as voltage, current, or resistance. Also called photocell.

pitch — Of a vehicle, an angular displacement about an axis parallel to the lateral axis of the vehicle. Rotation in the vertical plane.

pitch axis — A lateral axis through an aircraft or missile about which the body pitches.

power	Rate of doing work or of expending energy. Electric power is expressed in watts.
power density	Pertaining to the power radiated per unit area through a hypothetical surface at some specified distance from an antenna.
precision guided munitions	Missiles, bombs, projectiles, warheads, etc. that achieve a CEP equal to or less than their lethal radius through the use of guidance and control.
projectile	Any object, especially a missile, fired, thrown, launched, or otherwise projected in any manner, such as a bullet, a guided rocket, missile, pilotless airplane, etc. Originally, an object, such as a bullet or artillery shell, projected by an applied external force.
propagation	The spreading abroad or sending forward, as of radiant energy.
proportional control	Control of a missile in which control surface deflection is proportional to the commands. Compare bang-bang control.
proportional navigation	The control of the angular rate of the velocity vector of a vehicle in proportion to the apparent relative angular velocity of its moving target.
proximity fuze	A fuze that detonates the warhead by sensing the nearness of a target.
pulse	(1) A variation of a quantity whose value is normally constant or zero; this variation is characterized by a rise and a decay, and has a finite duration. A controlled burst of energy. (2) In electronics, a waveform having a short rectangular shape. (3) In radar, short periodic pulses of the carrier transmitter to measure the time required for the energy to travel to the target and return to the radar.
pulse amplitude	A general term indicating the magnitude of a pulse.
pulse code	A sequence of pulses so modulated as to represent information.
pulsed Doppler system	A pulse radar system which utilizes the Doppler effect for obtaining information about the target (usually its velocity).
pulse modulation	Modulation of a carrier by a pulse train.
pulse packet	In radar, the volume of space occupied by the radar pulse energy.

pulse radar — A type of radar, designed to facilitate range measurement, in which the transmitted energy is emitted in short periodic pulses. Also called pulsed radar. Compare continuous wave radar.

pulse train — A sequence of pulses.

R

radar — (From radio detection and ranging.) (1) A method, system, or technique of using beamed, reflected, and timed radio waves for detecting, locating, or tracking objects (such as aircraft); for measuring range and direction in any of various activities, such as air traffic control, air defense, fire control, or guidance. (2) The electronic equipment or apparatus used to generate, transmit, receive, and, usually, to display the radar returns; a radar set.

radar cross section (RCS or σ) — Defined as 4π times the ratio of the power per unit solid angle scattered back toward the transmitter, to the power per unit area striking the target. Also, equal to the cross section area of a conducting sphere which produces the same power return as the target. Usually measured in square meters.

radar horizon — The angle of elevation at which the beam from a radar antenna is intercepted by the earth's horizon.

radar reflectivity — In general, the measure of the efficiency of a radar target in intercepting and returning a radar signal. It depends upon the size, shape, aspect, and dielectric properties at the surface of the target.

radar scan — The searching motion of a radar beam in any of various path configurations; the pattern of the motion of a radar beam.

radial velocity — In radar, that vector component of the velocity of a moving target that is directed toward or away from the radar.

radiance — In radiometry, a measure of the intrinsic radiant intensity emitted by a radiator in a given direction. It is the irradiance (radiant flux density) produced by radiation from the source upon a unit surface area oriented normal to the line between source and receiver, divided by the solid angle subtended by the source at the receiving surface.

radiancy	The rate of radiant energy emission from a unit area of a source in all the radial directions of the overspreading hemisphere.
radiant energy	The energy of any type of electromagnetic radiation. Also called radiation.
radiant flux	The rate of flow of radiant energy.
radiant flux density	= radiant flux per unit area. When applied to a source it is called radiancy. When applied to a receiver it is called irradiance or irradiancy.
radiation	The process by which electromagnetic energy is propagated through free space by virtue of joint undulatory variations in the electric and magnetic fields in space.
radiation pattern	A graphical representation of the radiation of our antenna as a function of direction. Also called antenna pattern.
radio	(1) Communication by electromagnetic waves without a connecting wire. (2) Pertaining to radio frequency, as in radio wave.
radio frequency (RF)	(1) A frequency at which coherent electromagnetic radiation of energy is useful for communication purposes. (2) Specifically, the frequency of a given radio carrier wave.
radio guidance system	A guidance system that uses radio signals to guide an aircraft or missile in flight.
radiometer	An instrument for detecting and, usually, measuring radiant energy emitted from various objects.
radio waves	Waves produced by oscillation of an electric charge at a frequency useful for radio communication.
radome	(From radar dome) A dielectric housing for a radar antenna. Usually forming the nose of a radar guided missile or radar carrying aircraft.
range gate	An electronic circuit, generally in a tracking radar, that passes the target echo pulse to angle tracking (or other) circuits and suppresses signals occurring outside the gate width. The range gate is usually automatically controlled to follow the desired target echo, known as range tracking.

range gating	The use of circuits in a radar to suppress signals from all targets falling outside selected range limits.
rate gyro	A single-degree-of-freedom gyro having primarily elastic restraint of its spin axis about the output axis. In this gyro an output signal is produced by gimbal angular displacement, relative to the base, which is proportional to the angular rate of the base about the input axis.
ray	An elemental path of radiated energy; or the energy following this path. It is perpendicular to the phase fronts of the radiation.
reaction engine	An engine that develops thrust by its reaction to a substance ejected from it; specifically an engine that ejects a jet of gases by burning fuel within the engine.
real time	Time in which reporting on events or recording of events is simultaneous with the events.
received power	In radar, the power of a target signal received at the radar antenna.
receiver	An instrument used to detect the presence of and to determine the information carried by electromagnetic radiation. A receiver includes circuits designed to detect, amplify, rectify, and shape the incoming radio frequency signals received at the antenna in such a manner that the information containing component of this received energy can be delivered to the desired indicating, recording, or control equipment.
recognition	The psychological (or electronic) process in which an observer so interprets the visual stimuli (target signature) received from a distant object that a correct conclusion is formed as to the exact nature of that object. Used as in target recognition. Recognition is a more subtle phenomenon than the antecedent step of detection, for the latter involves only the simpler process of interpreting received stimuli to the extent of concluding that an object is present at some distance from the observer.
reflection	The process whereby a surface of discontinuity turns back a portion of the incident radiation into the medium through which the radiation approached.

refraction — The process in which the direction of propagation is changed as the result of a change in density within the propagating medium, or as the energy passes through the interface representing a density discontinuity between two media. In the first instance the rays undergo a smooth bending over a finite distance. In the second case the index of refraction changes through an interfacial layer that is thin compared to the wavelength of the radiation; thus, the refraction is abrupt, essentially discontinuous.

relative movement — Motion of one object or body measured relative to another. Also called relative motion.

resolution — (1) The ability of a film, a lens, a combination of both, or a television system to render barely distinguishable a standard pattern of black and white lines. (2) In radar, the minimum angular separation, at the antenna, at which two targets can be distinguished (a function of beamwidth); or the minimum range separation at which two targets at the same azimuth can be separated (equal to one-half the pulse length). (3) Of a gyro, a measure of response to small changes in input; the minimum input change that will cause a detectable change in the output.

resonance — The phenomenon of amplification of a free wave or oscillation of a system by a forced wave.

resonant frequency — A frequency at which resonance exists.

response — Of a device or system, the motion (or other output) resulting from an excitation under specified conditions.

reticle — A system of lines, wires, etc. placed in the focal plane of an optical instrument to serve as a reference.

rocket — A projectile, pyrotechnic device, or flying vehicle propelled by a rocket engine.

rocket engine — A reaction engine that contains within itself, or carries along with itself, all the substances necessary for its operation or for the consumption or combustion of its fuel, not requiring intake of any outside substance.

roll	(1) The act of rolling; rotation or oscillatory movement of a missile about a longitudinal axis through the body. (2) The amount of this movement.
roll axis	A longitudinal axis through an aircraft or missile body about which the body rolls.

S

scanner	A mechanism for directing a radar or optical beam through space in order to search for or track a target.
scanning	The motion of a radar or optical beam when searching for or tracking targets.
scattering	The process by which small particles suspended in a medium of a different index of refraction diffuse a portion of the incident radiation in all directions. In scattering, no energy transformation results, only a change in the spatial distribution of the radiation. Also called scatter.
scattering cross section	The hypothetical area normal to the incident radiation that would geometrically intercept the total amount of radiation actually scattered by the scattering particles. It is also defined, equivalently, as the cross section area of an istropic scatterer (a sphere) which would scatter the same amount of radiation as the actual amount. Also called effective area.
search radar	A radar designed to search for targets.
seeker	Subsystem of homing missile that tracks the target of interest.
semiactive homing guidance	Guidance in which a missile is directed toward its destination by means of information received from the destination in response to transmissions from a source other than the missile.
sensitivity	The ability of electronic equipment to amplify a signal, measured by the minimum strength of signal input capable of causing a usable value of output. The lower the input signal for a usable output, the higher the sensitivity.

sensor
: The component of an instrument that converts an input signal into a quantity which is measured by another part of the instrument. Also called sensing element.

signal
: (1) A visible, audible, electrical, or other indication used to convey information. (2) The information to be conveyed over a communication system. (3) Any carrier of information; opposed to noise.

signal-to-noise ratio (SNR or S/N)
: A ratio which measures the comprehensibility of a data source or transmission link, usually expressed as the root-mean-square signal amplitude divided by the root-mean-square noise amplitude. The higher the S/N ratio, the less interference with reception.

simple harmonic quantity
: A periodic quantity that is a sinusoidal function of the independent variable. Thus,

$$y = A \sin (\omega t + \phi)$$

where y is the simple harmonic quantity; A is the amplitude; ω is the angular frequency; t is the independent variable; and ϕ is the phase of the oscillation.

slenderness ratio
: A dimensionless number expressing the ratio of a rocket vehicle length to its diameter.

solid angle
: A portion of the whole of space about a given point, bounded by a conical surface with its vertex at that point and measured by the area cut by the bounding surface from the surface of a sphere of unit radius centered at that point. See steradian.

sonar
: (From sound, navigation, and ranging.) A method or system, analogous to radar used under water, in which high frequency sound waves are emitted so as to be reflected back from objects, and used to detect the objects of interest.

spectrum
: Short for electromagnetic spectrum or for any part of it used for a specific purpose as the radio spectrum (10 KHz to 300 GHz).

specular reflection
: Reflection in which the refected radiation is not diffused; reflection as from a mirror.

spiral scanning
: Scanning in which the direction of maximum radiation describes a portion of a spiral. The rotation is always in one direction.

stability	The property of a body, as an aircraft or rocket, to maintain its attitude or to resist displacement, and, if displaced, to develop forces and moments tending to restore the original condition.
stable platform	A gyroscope device so designed as to maintain a plane of reference in space regardless of the movement of the vehicle carrying the stable platform.
stealth	A design concept for reducing the radar cross section of a target. May be implemented by shaping the target to reduce the radar cross section, coating it with radar absorbing materials, or using non-conducting materials for construction.
steradian	The unit solid angle which cuts unit area from the surface of a sphere of unit radius centered at the vertex of the solid angle. There are 4π steradians in a sphere.
system	Any organized arrangement in which each component part acts, reacts, or interacts in accordance with an overall design inherent in the arrangement. Specifically, a major component of a given vehicle such as a propulsion system or a guidance system.

T

tactical air navigation (TACAN)	A two dimensional navigation system which provides azimuth and distance to a fixed ground station for navigation of piloted aircraft.
tail fin	A fin at the rear of a rocket or missile to provide stability or control.
tangent ogive	An ogive whose circular-arc contours have their centers on a line normal to the axis at the base of the ogive, the arcs thus being tangent to the surface of the cylindrical body behind the ogive. See ogive.
target	(1) Any object, point, etc. toward which something is directed. (2) An object which reflects a sufficient amount of a radiated signal to produce an echo signal on detection equipment.
target acquisition	The process of optically, manually, mechanically, or electronically orienting a tracking system in the direction and range to lock-on a target.

target signal	The radar energy returned to a radar by a target. Also called echo.
target signature	The signal radiated or reflected by a target that has characteristic fluctuations in time, frequency, or space that can be sensed remotely. Used to detect or identify a target.
terminal guidance	Guidance from an arbitrary point, at which midcourse guidance ends, to the destination.
thermal emission	The process by which a body emits electromagnetic radiation as a consequence of its temperature only.
thermal noise	The noise at radio frequencies caused by thermal agitation in a dissipative body. Also called Johnson noise.
thermal radiation	The electromagnetic radiation emitted by any substance as the result of the thermal excitation of its molecules. Thermal radiation ranges in wavelength from the longest infrared radiation to the shortest ultraviolet radiation.
threshold	Generally, the minimum value of a signal that can be detected by the system or sensor under consideration.
thrust	The pushing or pulling force developed by an aircraft engine or a rocket engine.
torque	About an axis, the product of a force and the distance of its line of action from the axis.
track	(1) The path or actual line of movement of an aircraft, rocket, etc. over the surface of the earth. It is the projection of the flight path on the surface. (2) To observe or plot the path of something moving, such as an aircraft or rocket, by one means or another, as by telescope or by radar. (3) To follow a desired path.
tracking	The process of following the movements of an object. This may be done by keeping the reticle of an optical system or a radar beam on the object, by plotting or measuring its bearing and distance, or by a combination of the two. May be implemented manually or automatically.
tracking antenna	A directional antenna system which changes in position, or characteristics, automatically or manually to follow the motions of a moving signal source.

tracking filter An electronic device for attenuating unwanted signals while passing desired signals.

tracking gate An electronic circuit that separates the desired target signal from all other signals received. It automatically follows (tracks) and passes the target signals to other portions of the receiver to allow automatic target tracking. A range or velocity gate.

tracking radar A radar used for following a target.

trajectory In general, the path traced by any body moving as a result of an externally applied force, considered in three dimensions.

transducer A device capable of being actuated by energy from one or more transmission systems or media and of supplying related energy to one or more other transmission systems or media, as a microplane, photo cell, rate gyro, etc.

transmission loss The reduction in the magnitude of some characteristic of a signal between two stated points in a transmission system.

transmitter A device used for the generation of signals of any type and form which are to be transmitted.

turbulent flow Fluid motion in which random motions of parts of the fluid are superimposed upon a simple pattern of flow. All or nearly all fluid flow displays some degree of turbulence. The opposite is laminar flow.

U

ultraviolet radiation Electromagnetic radiation of shorter wavelength than visible radiation; roughly radiation in the wavelength interval from 100 to 4000 angstroms. Also called ultraviolet (UV).

umbilical cord Any of the servicing electrical or fluid lines between the launcher and missile employed before launch.

undamped natural frequency Of a mechanical system, the frequency of free vibration resulting from only elastic and inertial forces of the system.

V

vector Any quantity, such as force, velocity, or acceleration, which has both magnitude and direction at each point in space, as opposed to a scalar which has magnitude only.

vehicle Specifically, a structure, machine, or device such as an aircraft or rocket, designed to carry a burden through air or space; more restrictively, a rocket vehicle.

velocity (1) Speed. (2) A vector quantity equal to speed in a given direction.

velocity gate = speed gate. An electronic circuit in a Doppler radar system that tracks or passes the Doppler frequency of the target echo. Used to discriminate against other signals entering the radar.

velocity of light (symbol c) The velocity of propagation of electromagnetic radiation through a perfect vacuum; a universal dimensional constant equal to 299,792.5 ± 4 kilometers per second. Often approximated as 3×10^8 meters per second.

video Pertaining to the picture signals associated with television or radar displays. These are the signals after final detection or demodulation, generally having a bandwidth of a few megahertz.

Visible radiation Electromagnetic radiation lying within the wavelength interval to which the human eye is sensitive, the spectral interval from approximately 0.4 to 0.7 microns (4000 to 7000 angstroms).

W

warhead The part of a missile carrying the explosive or other charge intended to damage the target.

watt (W) The unit of power in meter, kilogram, second, ampere system; that power which produces energy at the rate of one joule per second.

wave A disturbance which is propagated in a medium in such a manner that at any point in the medium the quantity serving as a measure of disturbance is a function of the time, while at any instant the displacement at a point is a function of the position of the point.

waveform	The graphical representation of a wave, showing variation of amplitude with time.
wavelength (symbol λ)	In general, the mean distance between maximums (or minimums) of a roughly periodic pattern. Specifically, the least distance between particles moving in the same phase of oscillation in a wave disturbance.
wave train	A limited series of waves caused by a periodic disturbance of short duration, e.g., the radio frequency waves in a single pulse, or a succession of pulses themselves.
white noise	A sound or electromagnetic wave whose spectrum is continuous and uniform as a function of frequency.

Y

yaw	(1) The rotational or oscillatory movement of an aircraft, missile, or the like about a vertical axis. (2) The amount of this movement, i.e., the yaw angle. (3) To cause to rotate about a vertical axis. (4) To rotate or oscillate about a vertical axis.
yaw axis	A vertical axis through an aircraft, rocket, or similar body, about which the body yaws.

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THE TACTICAL WEAPON GUIDANCE AND CONTROL INFORMATION ANALYSIS CENTER (GACIAC)

GACIAC is a DoD Information Analysis Center operated by IIT Research Institute under the technical sponsorship of the Joint Service Guidance and Control Committee with members from OUSDRE, Army, Navy, Air Force, and DARPA. The U.S. Army Missile Command provides the Contracting Officer's Technical Representative. Its mission is to assist the tactical weapon guidance and control community by encouraging and facilitating the exchange and dissemination of technical data and information for the purpose of effecting coordination of research, exploratory development, and advanced technology demonstrations. To accomplish this, GACIAC's functions are to:

1. *Develop a machine-readable bibliographic data base--currently containing over 27,000 entries;*
2. *Collect, review, and store pertinent documents in its field of interest--the library contains over 1500 reports in hard copy, and approximately four thousand more on microfiche;*
3. *Analyze, appraise and summarize information and data on selected subjects;*
4. *Disseminate information through the GACIAC Bulletin, bibliographies, state-of-the-art summaries, technology assessments, handbooks, special reports, and conferences;*
5. *Respond to technical inquiries related to tactical weapon guidance and control; and*
6. *Provide technical and administrative support to the Joint Service Guidance and Control Committee (JSGCC).*

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